Modeling Open and Hidden Heavy Flavor Production in Realistic Medium

RHIC & AGS Annual Users' Meeting 2016

Brookhaven National Laboratory (USA)

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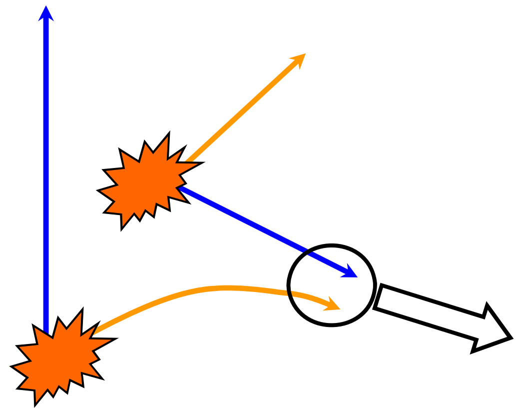
with

J. Aichelin, H. Berrehrah, R.Bierkandt, M. Bluhm, E. Bratkovskaya, W. Cassing, Th, Gousset, V. Guiho, B. Guiot, R. Katz, M. Nahrgang, V. Ozvenchuk, A. Peshier, M. Rohrmoser, S. Vogel, K. Werner,…

Early 2000:Thews, Rafelski & Schroedter

Main focus: « …a direct extrapolation of anomalous suppression (of J/ψ) from the SPS energy range could be supplanted by a new formation mechanism fueled by the presence of multiple pairs of charm quarks in each nuclear collision at sufficiently high energy».



Recombination of exogenous quarks, spatially uncorrelated => quadratic dependence in N_c. Indeed, for a given c-quark, the probability *P* to combine with a cbar quark to produce a J/ψ is:

$$P \,\alpha\, \frac{N_{\bar{c}}}{N_{\bar{u},\bar{d},\bar{s}}} \,\alpha\, \frac{N_{c\bar{c}}}{N_{\text{ch}}}.$$

True for each available c-quark (N_c all together) => number of J/ψ's through exogenous kinetic (re)combination » :

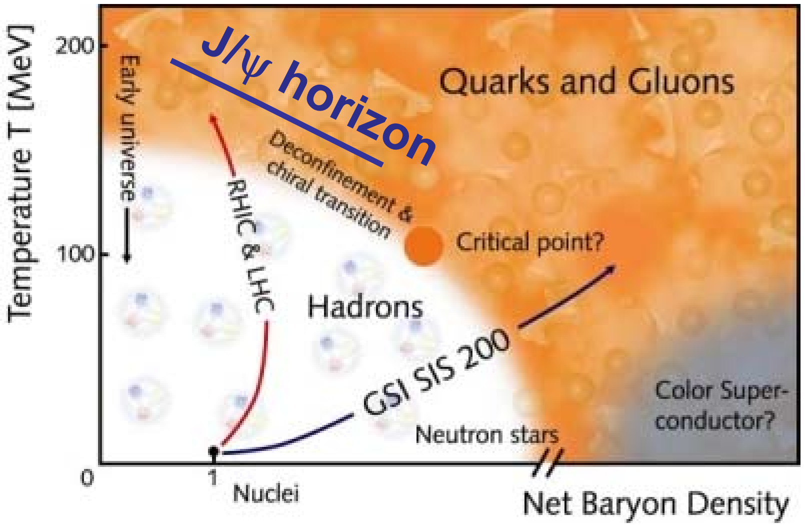
$$N_{J/\psi} \,\alpha\, \frac{N_{c\bar{c}}^2}{N_{\text{ch}}}$$

Precise α-value: depends on the dynamics of the system

TRS: kinetic equation $$\frac{dN_{J/\psi}(\tau)}{d\tau} = \frac{\lambda_{\text{F}}(\tau)}{V(\tau)} N_c N_{\bar{c}} - \lambda_{\text{D}}(\tau)\rho_{\text{g}}(\tau) N_{J/\psi}(\tau)$$

kinetic recombination within QGP

Even more interesting: momentum distribution could come with the Temperature at which those quarkonia are produced (beyond FO horizon)



Main caveat: as kinematic (re)combination is local in space-time and in momentum, the total number of produced J/ψ strongly depends on phase-space distribution of c-quarks (some assumptions used in TRS and then later in Thews and Mangano)

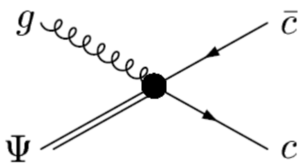
Some global view of our model development

2002: motivation for recombination of c and cbar J/Ψ using dynamical c/cbar distribution

Mid 2004:Gossiaux, Aichelin and Guiho

Ingredients of our calculation:

1. dissociation evaluated though g+J/ψ -> c+cbar cross section (Bhanot-Peskin)



$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0) - 1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega - \varepsilon(0))$$

2. (Re)combination evaluated through detailed balance mechanism.
3. Fokker Planck equation for heavy quark transport.
4. Transport coefficients evaluated according to Landau's treatment (so-called "grazing approximation" (as in Svetitsky 87, Mustafa 97) + LO qQ->qQ and gQ->gQ elastic cross section evaluated in-vacuum with fixed α_s and some regulator μ.
5. Some "soft" dissociation temperature above which no quarkonia formation is possible (following Matsui and Satz)
6. All of this implemented in a local transport approach.

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2004: 1rst version of the model

Elastic; Fixed αs; naïve regulator (T); cranking coefficient K

HF Eloss

Medium

Kolb Heinz: ideal hydro; smooth initial conds

System

AA

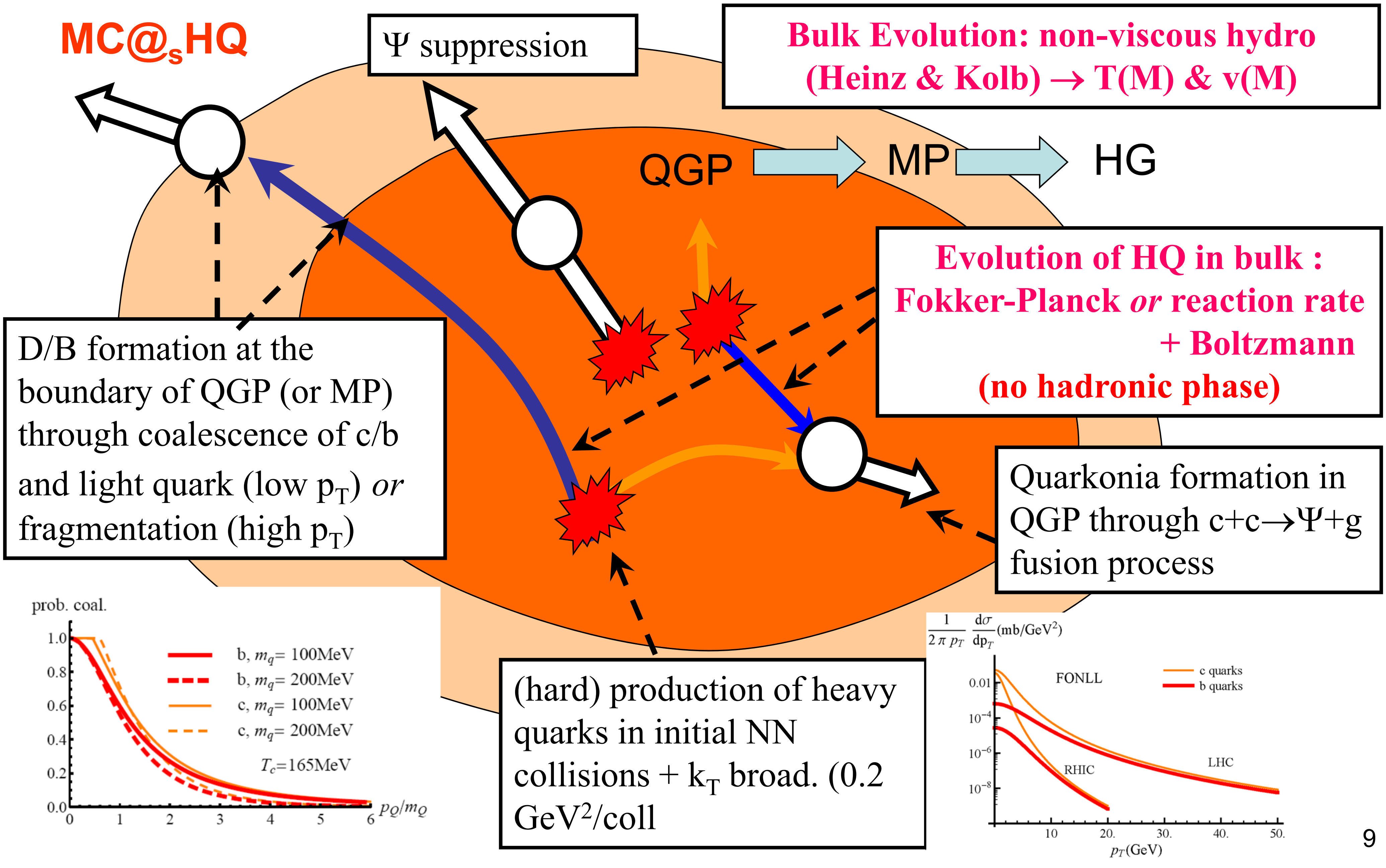
Kinetic treatment

Fokker Planck with imposed Einstein relation

Quarkonia physics

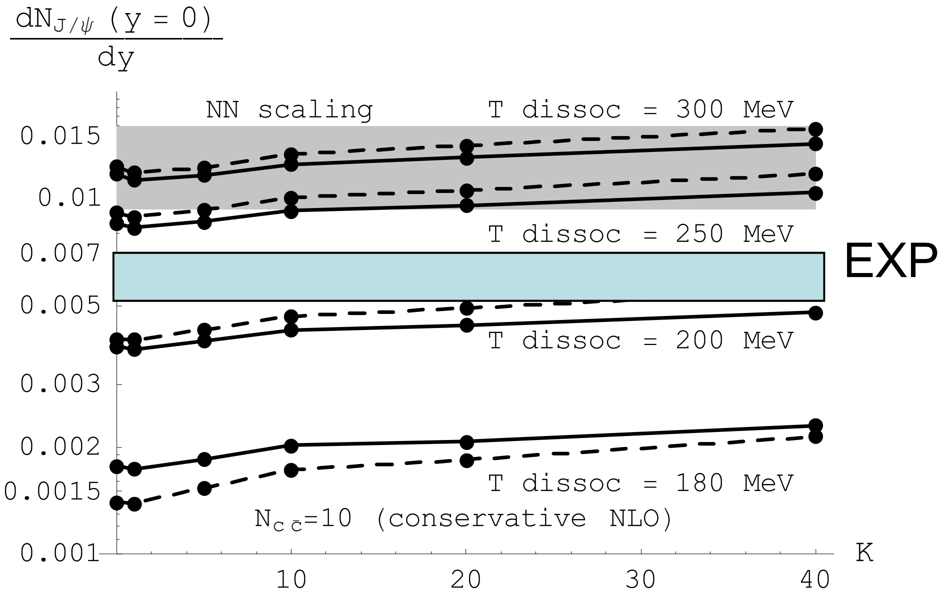
q+$\Phi\leftrightarrow$c+cbar à la Bhanot-Peskin + dissociation above T_{dis}

Schematic view of the global framework



Results from the calculations (2004)

J/ψ production in Au-Au, b=0, RHIC, mid rapidity



—— Heinz & Kolb's hydro

- - - No radial exp. hydro

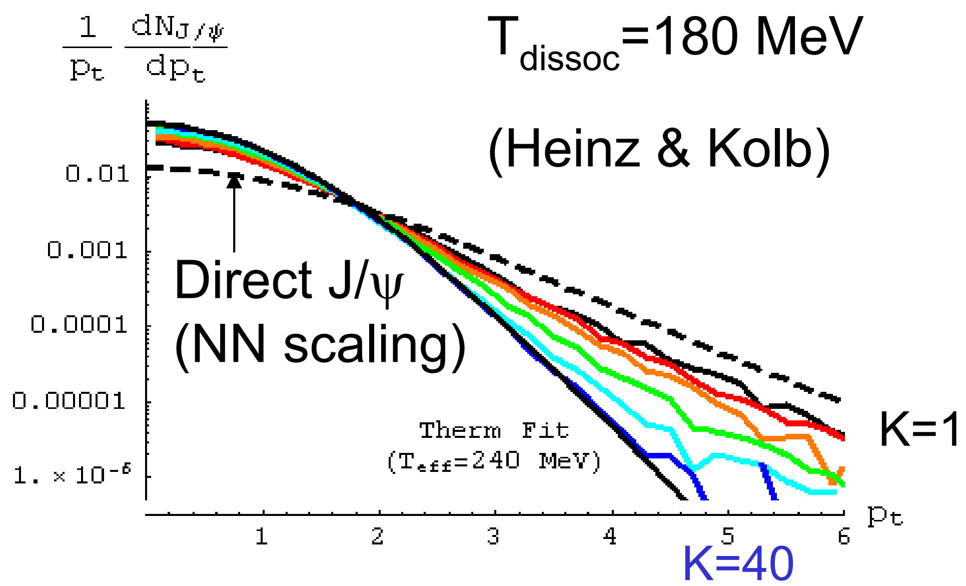
- N_c and T_{dissoc} : key parameters to explain global numbers.
- Larger thermalisation of c-quarks (larger K) leads to moderate increase of J/ψ production.

K: overall cranking factor of the FP coeff. A & B

$$\frac{\partial f}{\partial t} = \vec{\nabla}_p \left[\vec{A} f + \vec{\nabla}_p \left(\overleftrightarrow{B} f \right) \right]$$

Larger K => larger thermalization => smaller effective T of the c-quark distribution.

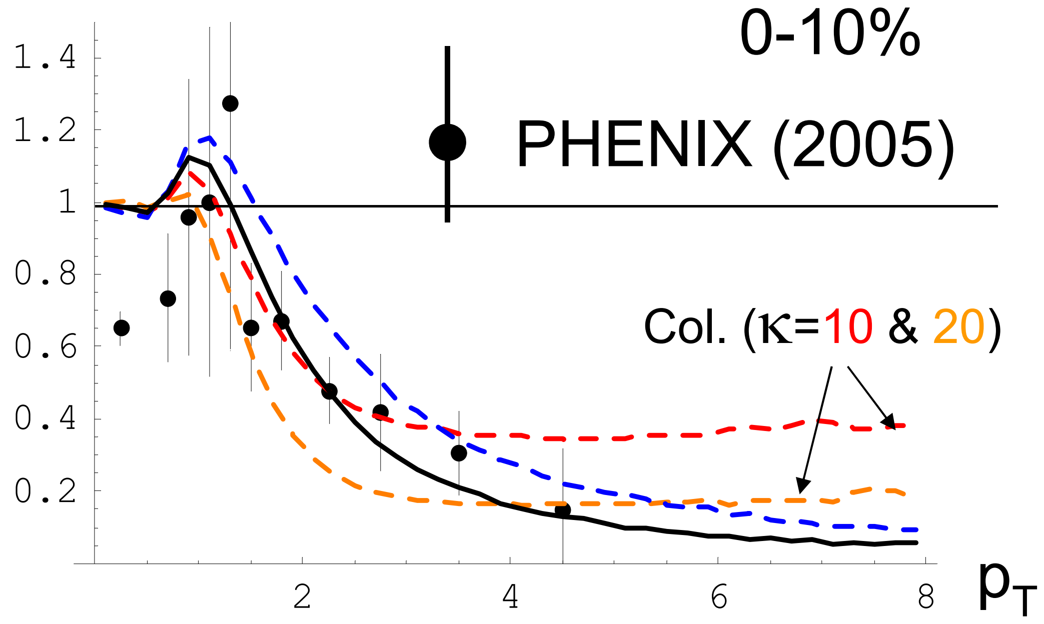
Differential p_T spectra reflects this effect (indeed seen later on by PHENIX) →



2000 -> 2005: growing interest for the measurement of open heavy flavor

Motivations: QGP tomography with well-controlled probes (initial distribution in phase space) that do not completely thermalize.

R_{AA} (Non photonic single electrons)



Suppression of decay electron from c and b quarks at “large” p_T due to HQ energy loss (quenching)… A big surprise, in fact !!!

Shape ok, but at the price of a large cranking factor K !!!

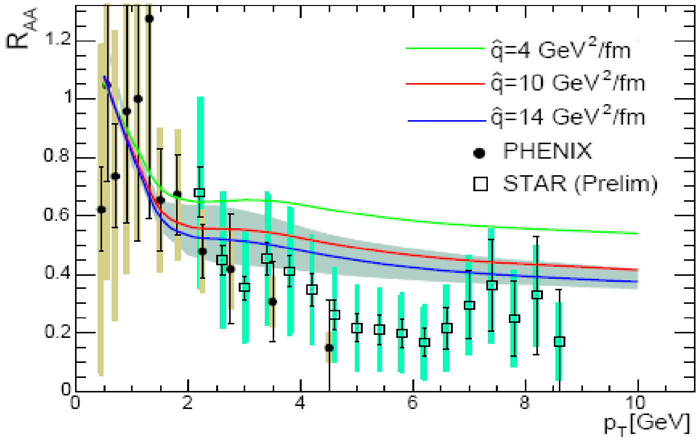
The weak to strong axis for HQ

"Naive" pQCD
(WHDG, ASW,…)
$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

"Optimized" pQCD
(ok with pions)

So-called "Failure of pQCD approach" aka "the non photonic single electron puzzle"

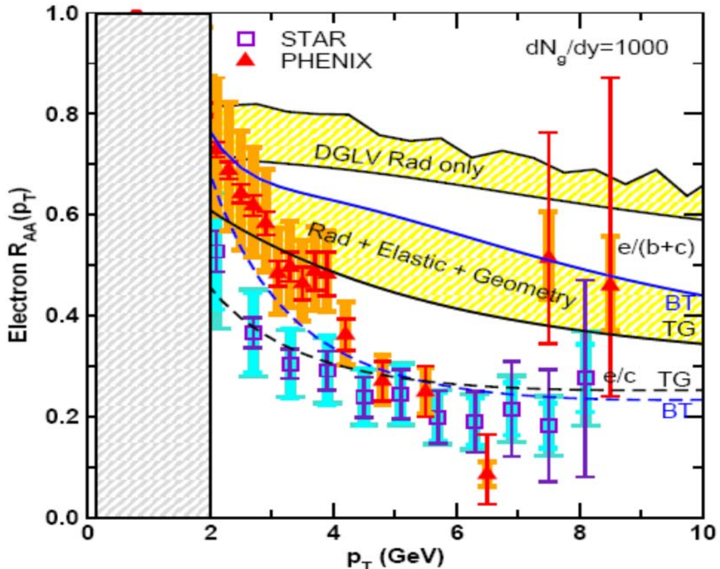
ASW (pure rad. energy loss; extended BDMPS)



Armesto et al Dainese, Phys. Rev D (hep-ph/0501225) & Phys.Lett. B637 (2006) 362-366 hep-ph/0511257

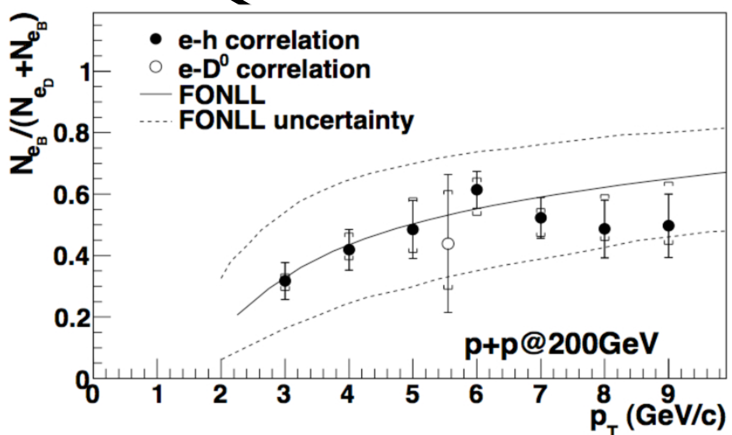
Conclude to rough agreement, subjected to b/c ratio in p-p

coll Eloss (BT and TG) + radiative Eloss



WHDG

Beauty is the problem… but beauty is found to contribute



M Aggarwal et al, STAR, PRL 105 202301

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2004: 1rst version of the model: **HF distrib matters**

HF Eloss

Elastic; Fixed αs; naïve regulator (T); cranking coefficient K

upgrade

Medium

Kolb Heinz: ideal hydro; smooth initial conds

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q+$\Phi \leftrightarrow$c+cbar à la Bhanot-Peskin + dissociation above T_{dis}

2008: Revisited model for HQ energy loss (Aichelin & Gossiaux)

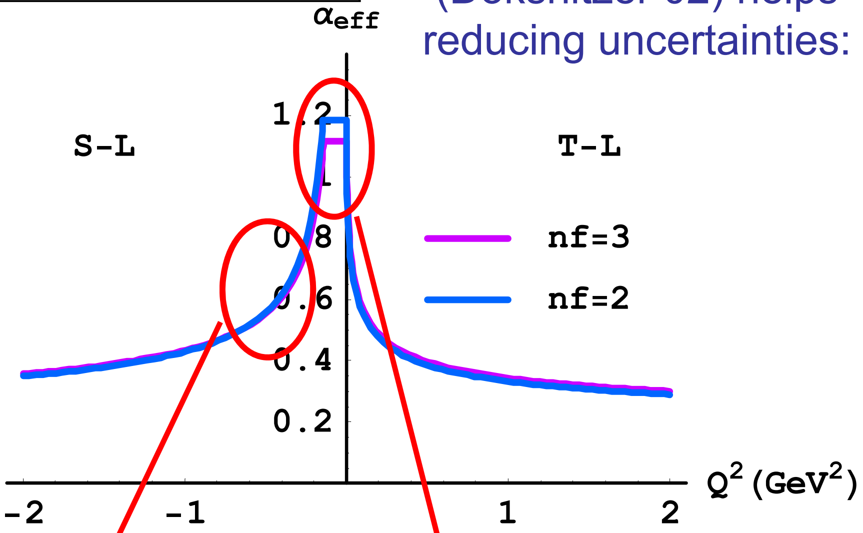
Motivations:

1) Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$ => need for running coupling constant… **but NOT pQCD**
2) From FP to Boltzmann transport => need for scattering amplitudes

Effective $\alpha_s(Q^2)$ (Dokshitzer 95, Brodsky 02)

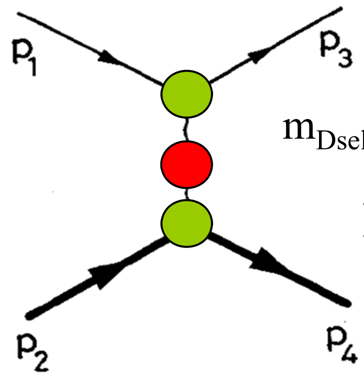
$$\frac{1}{Q_u}\int_{|Q^2|\leq Q_u^2} dQ\,\alpha_s(Q^2) \approx 0.5$$

“Universality constrain” (Dokshitzer 02) helps reducing uncertainties:



IR safe. Q^2 close to 0 does not contribute to Eloss

Large values for intermediate momentum-transfer => larger cross section

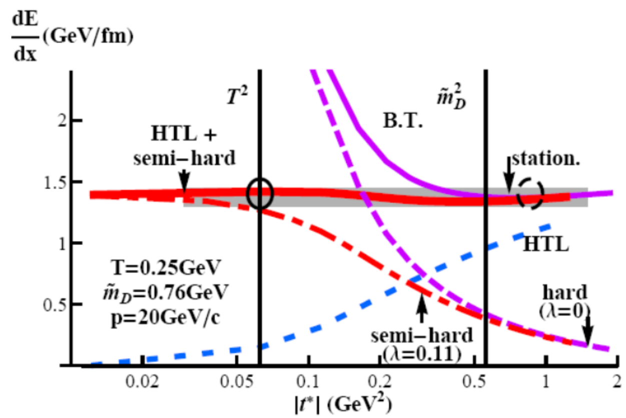


$$m_{\mathrm{Dself}}^2\,(T) = (1+n_f/6)\,4\pi\alpha_{\mathrm{eff}}(m_{\mathrm{Dself}}^2)\,T^2$$

$$\mathrm{prop} \propto \frac{1}{q^2 - \kappa m^2_{\mathrm{Dself}}(T)}$$

+ u and s channels

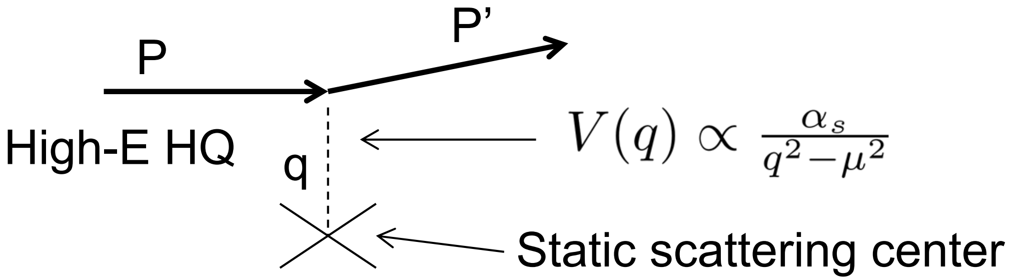
One gluon exchange effective propagator, designed in order to guarantee maximal insensitivity of dE/dx in Braaten-Thomas scheme



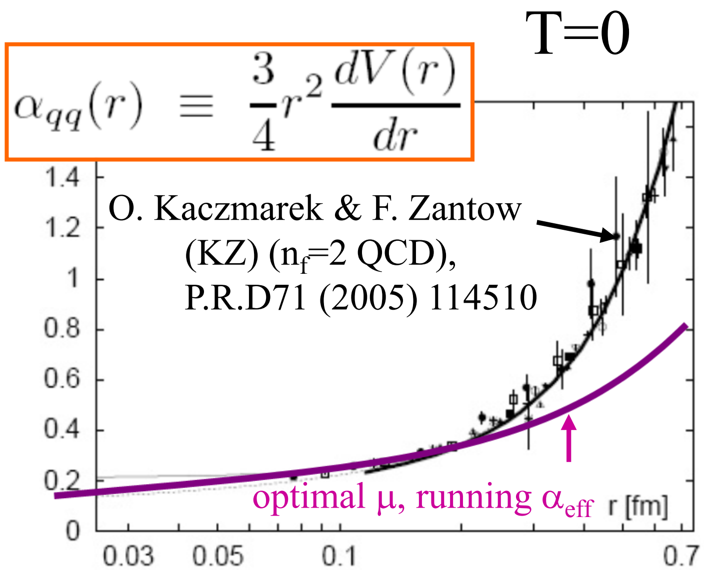
Insufficient control on energy loss theory

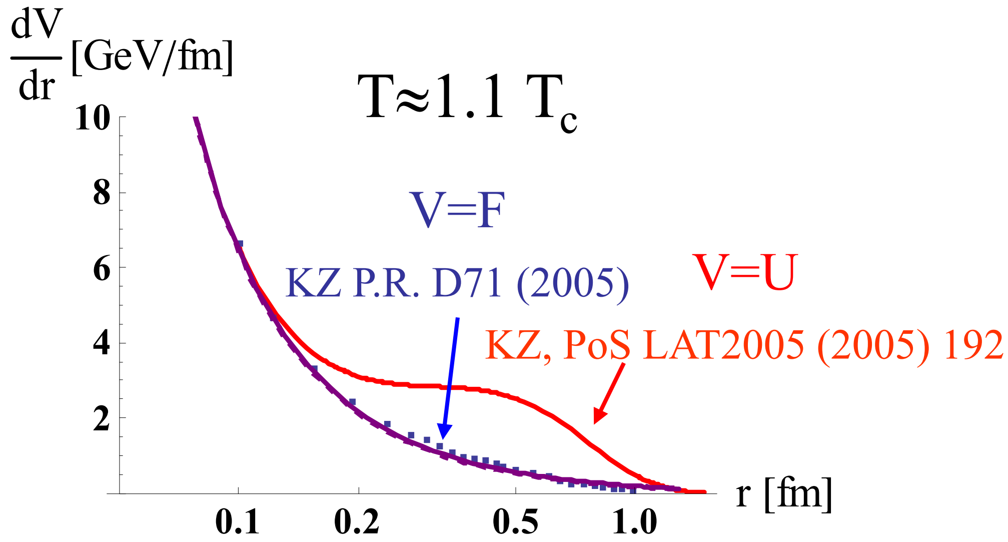
Non perturbative « corrections » even at large HQ energy

In most models:



Lattice QCD :





Our force is close to the one extracted from the free energy as a potential

=> Still allow for some global rescaling of the interactions rates: “K” fixed on experiment

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2008: 1rst open HF results for RHIC

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Elastic; running αs; regulator fixed on HTL; cranking coefficient K

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Boltzmann

upgrade

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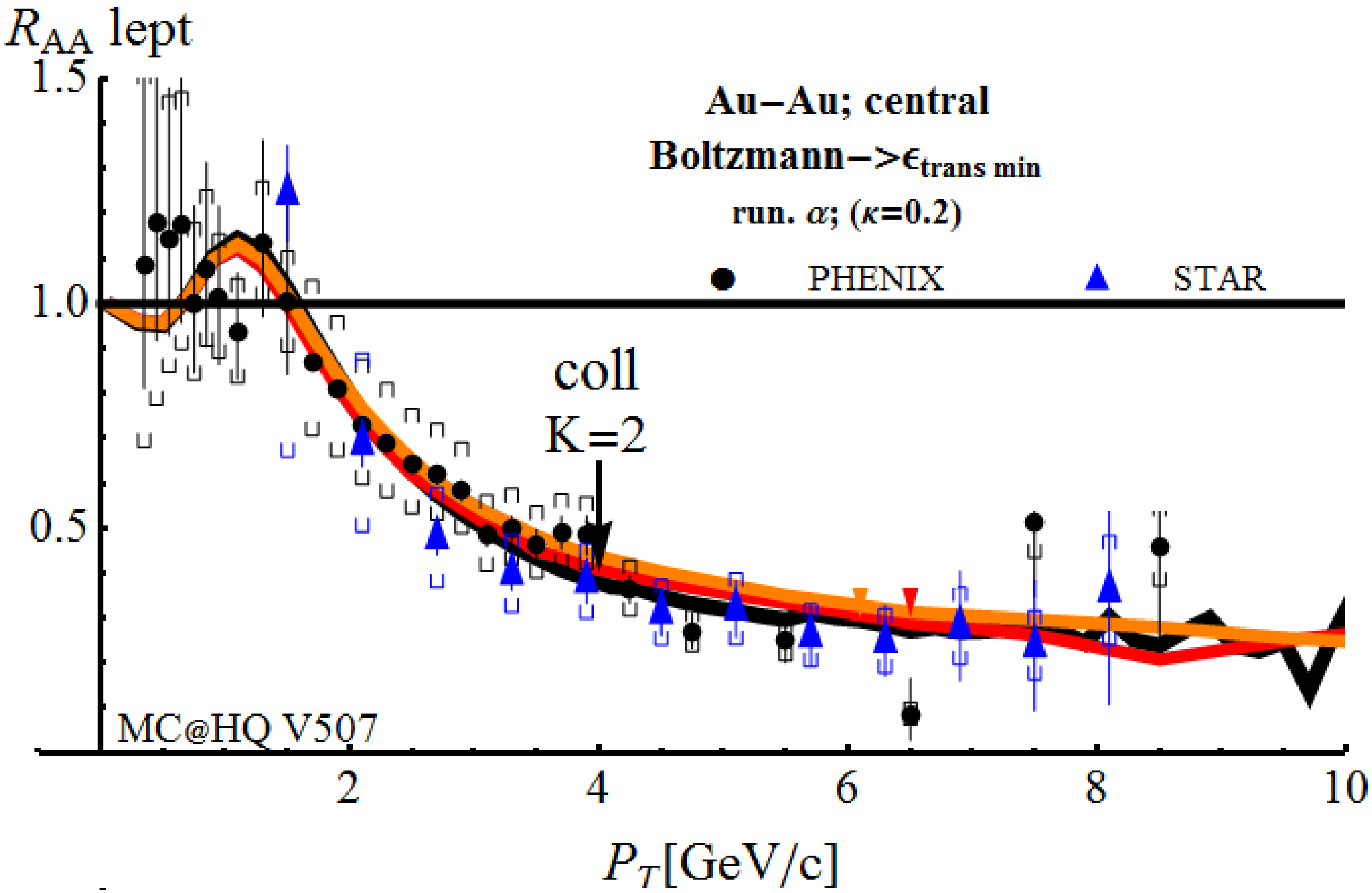
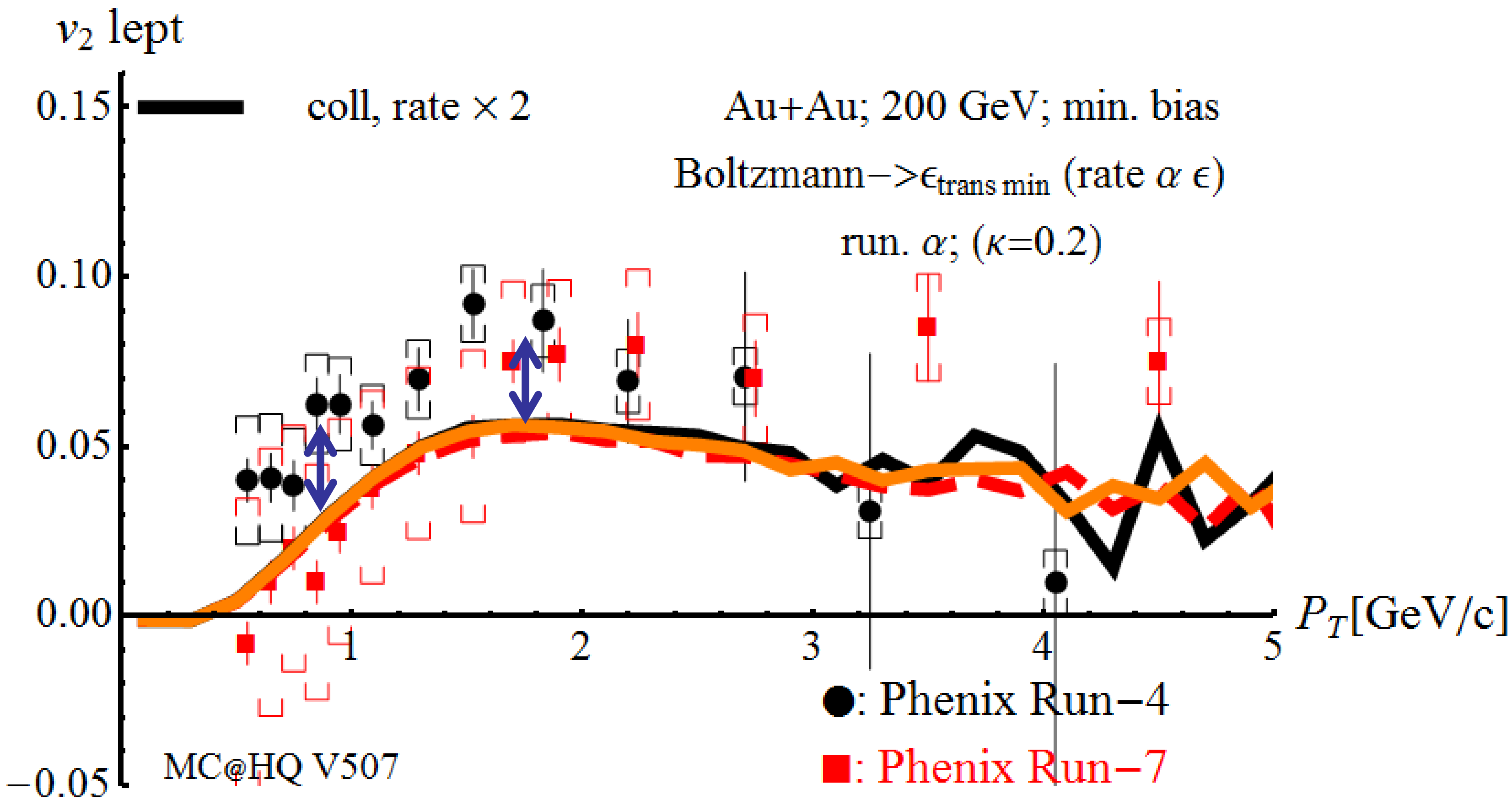
Elastic for leptons @ RHIC



Elastic for leptons @ RHIC



The weak to strong axis for HQ

"Naive" pQCD (WHDG, ASW,…)

$\hat{q} \approx 1\ \mathrm{GeV}^2/\mathrm{fm}$

So-called "Failure of pQCD approach" aka "the non photonic single electron puzzle"

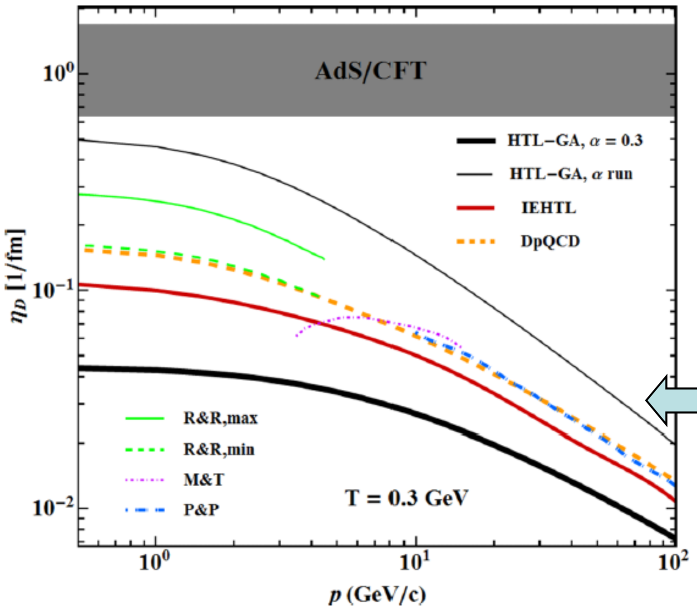
"Optimized" pQCD

Running $\alpha_s(T)$ and $m_{q/g}(T)$ (Berrehrah et al. DQPM model Frankfurt)

Running α_s (Peshier, Gossiaux & Aichelin, Uphoff & Greiner)

Distorsion of heavy meson fragmentation functions due to the existence of bound mesons in QGP, R. Sharma, I. Vitev & B-W Zhang

Bound states diffusion or non-perturbative, lattice potential scattering models (see R. Rapp and H Van Hees 0903.1096 [hep-ph] for a review)

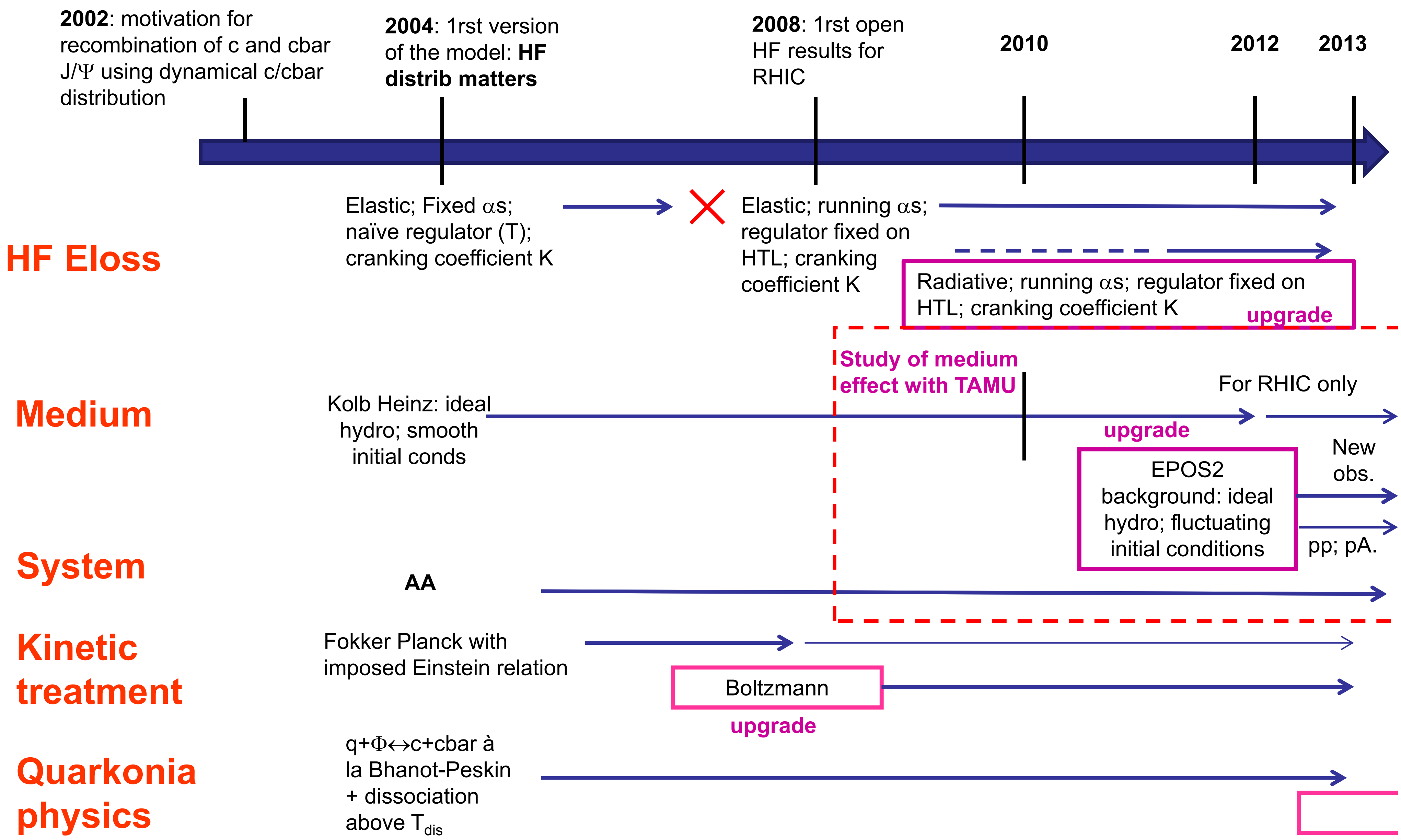


Big puzzle:

Several models containing either non perturbative features or tunable parameters are able to reproduce the HQ data, but many questions remain… and how to reconcile them all stays a challenge

ADS/CFT (akamatsu et al)

Some global view of our model development



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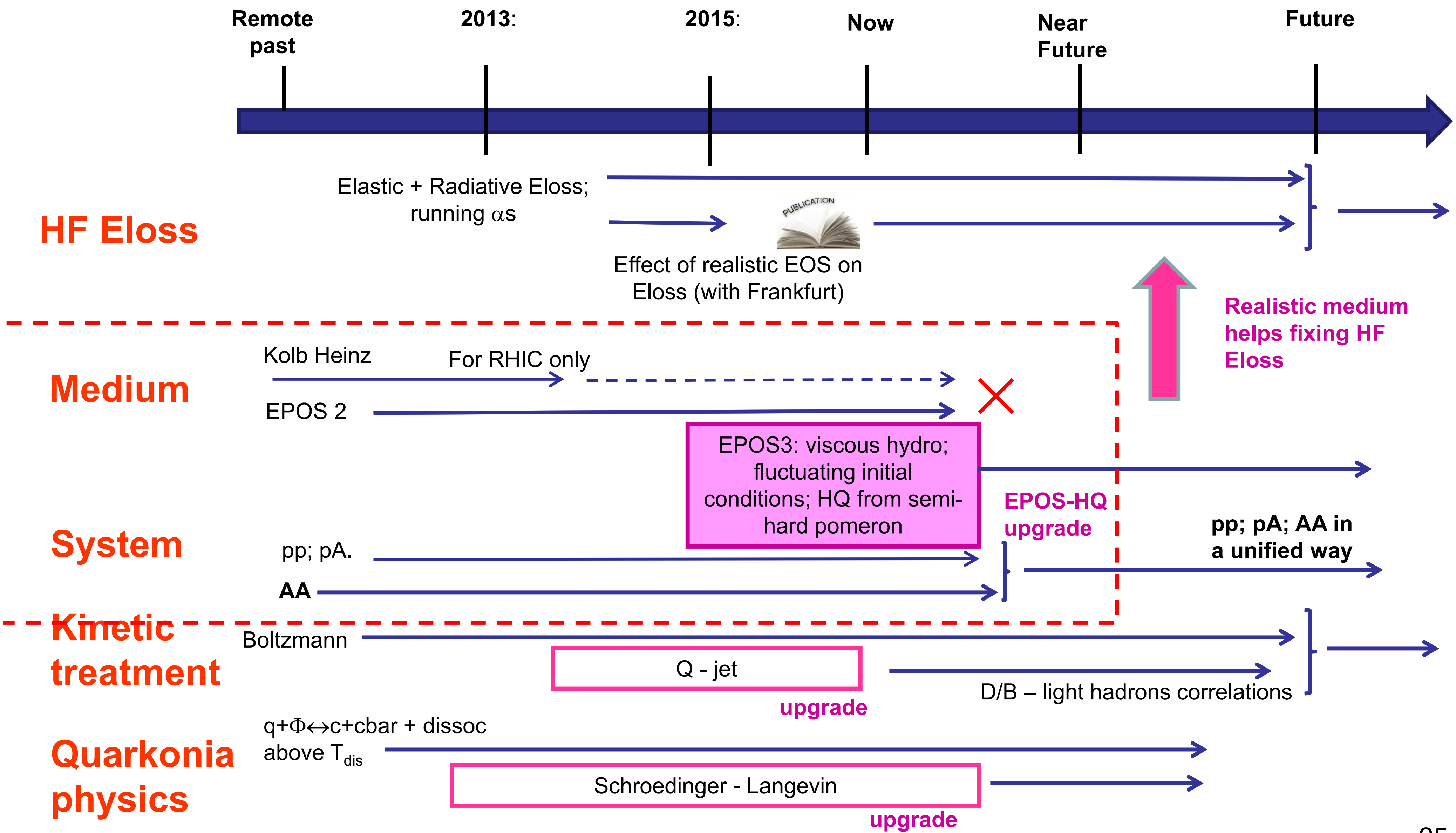


But we are not alone… … and it is good so

Some joint effort on HF:

Eur. Phys. J. C (2016) 76:107
DOI 10.1140/epjc/s10052-015-3819-5

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Review

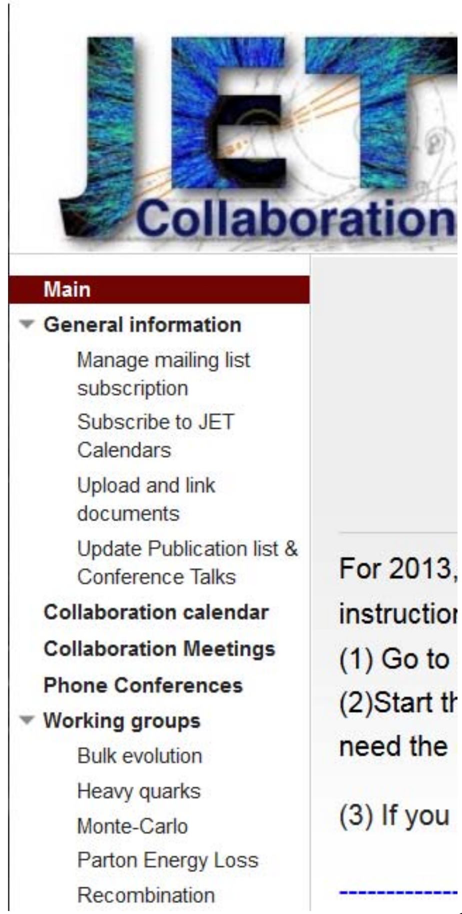
Heavy-flavour and quarkonium production in the LHC era: from proton–proton to heavy-ion collisions

A. Andronic[1], F. Arleo[2,3], R. Arnaldi[4], A. Beraudo[4], E. Bruna[4], D. Caffarri[5], Z. Conesa del Valle[6], J. G. Contreras[7], T. Dahms[8], A. Dainese[9], M. Djordjevic[10], E. G. Ferreiro[11], H. Fujii[12], P.-B. Gossiaux[13], R. Granier de Cassagnac[2], C. Hadjidakis[6], M. He[14], H. van Hees[15], W. A. Horowitz[16], R. Kolevatov[13,17], B. Z. Kopeliovich[18], J.-P. Lansberg[6], M. P. Lombardo[19], C. Lourenço[5], G. Martinez-Garcia[13], L. Massacrier[6,13,20,a], C. Mironov[2], A. Mischke[21,22], M. Nahrgang[23], M. Nguyen[2], J. Nystrand[24], S. Peigné[13], S. Porteboeuf-Houssais[25], I. K. Potashnikova[18], A. Rakotozafindrabe[26], R. Rapp[27], P. Robbe[20], M. Rosati[28], P. Rosnet[25], H. Satz[29], R. Schicker[30], I. Schienbein[31], I. Schmidt[18], E. Scomparin[4], R. Sharma[32], J. Stachel[30], D. Stocco[13], M. Strickland[33], R. Tieulent[34], B. A. Trzeciak[7], J. Uphoff[35], I. Vitev[36], R. Vogt[37,38], K. Watanabe[39,40], H. Woehri[5], P. Zhuang[41]

Sapore Gravis project (I3HP)… to be followed (HICHEF proposal in Hadron Physics Horizon)

Jet Collaboration HQ Working Group

(Initiative by XN Wang; 1rst meeting in Berkeley Jan 2016)



More to come:

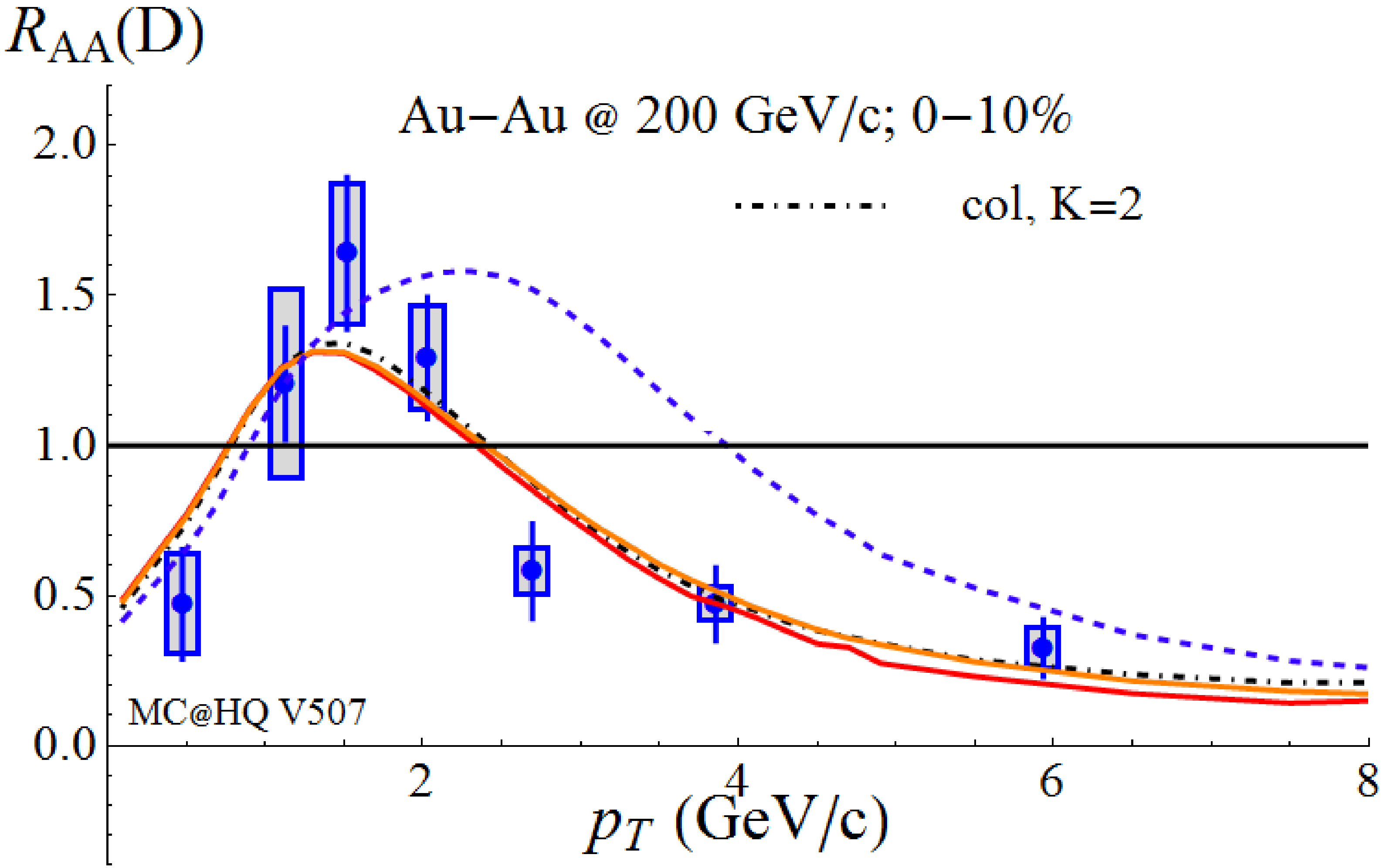
- Proposal for an EMMI RRTF on heavy-quarks in hot QCD matter (A. Andronic, R. Averbeck, P.B. Gossiaux, S. Masciocchi, R. Rapp)
- …

…Focusing on interrelated questions

- Consequences of the Elos model (including type of Eloss, coupling)… In particular: is it possible to pinpoint an “anomalous” behavior around Tc ?
- Consequence of the medium ?… of the EOS ?
- Mass hierarchy
- LHC vs RHIC and BES
- Smaller systems
- More sophisticated observables
- Constrains from the lattice
- Effect of hadronic phase
- ….

Elastic D mesons @ RHIC

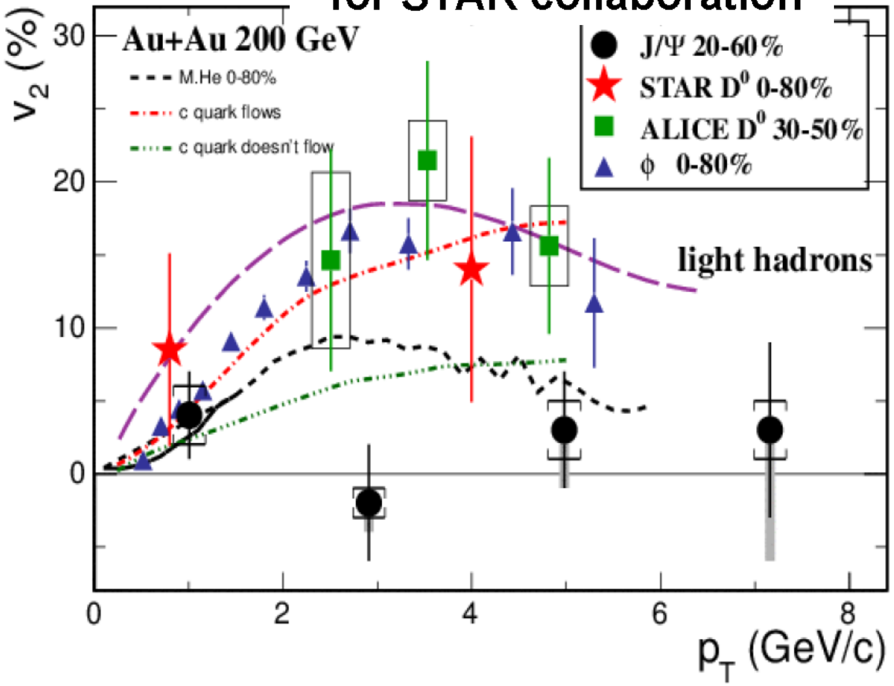
(Allow for some global rescaling of the rates: “K” fixed on experiment)

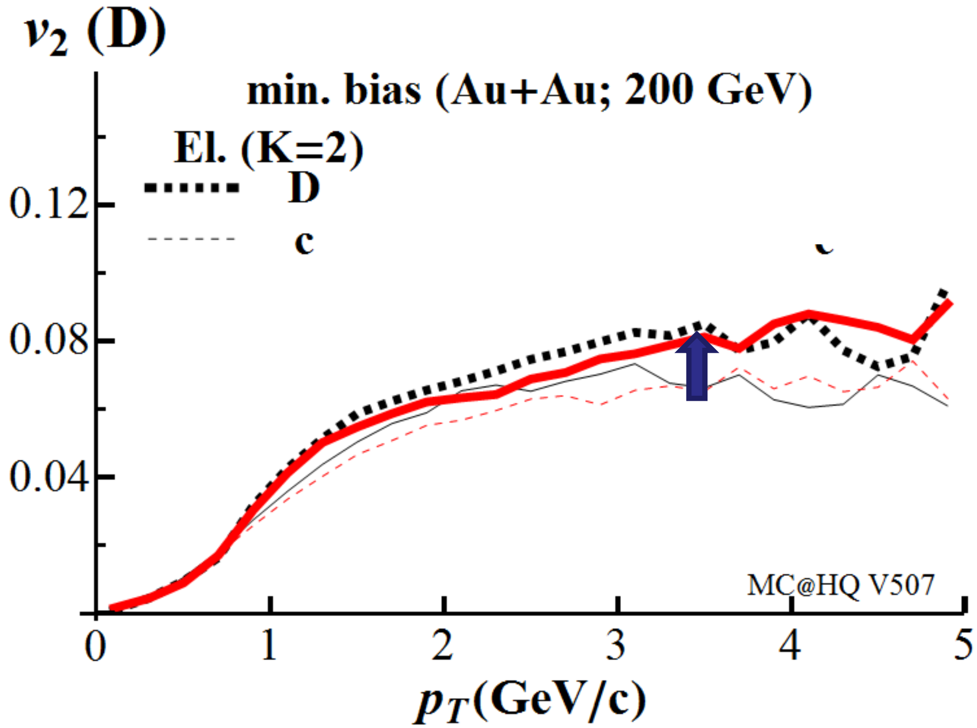


Elastic D mesons @ RHIC

Jaroslav Bielčík

for STAR collaboration





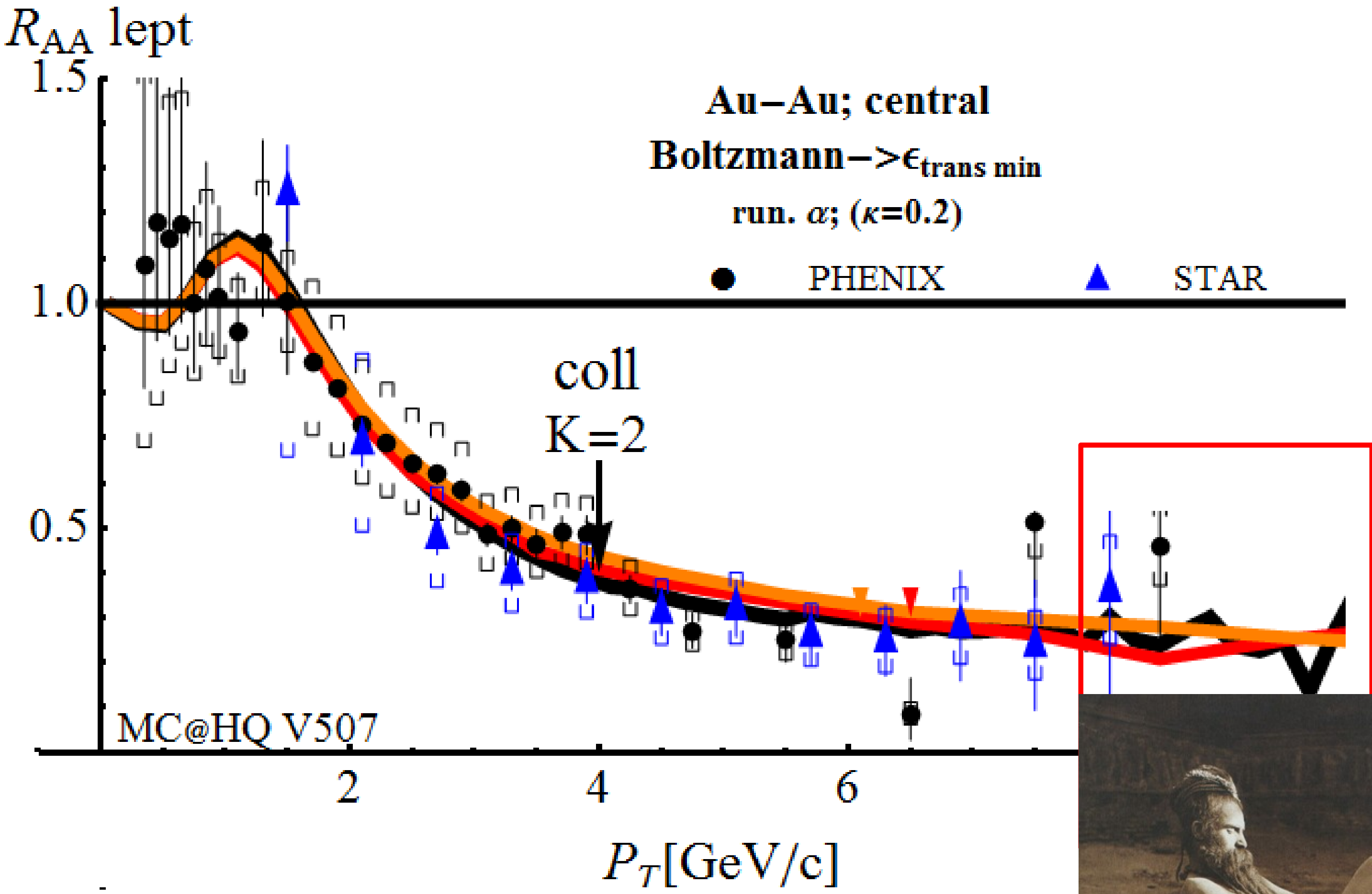
Rather little contribution from the light quark in our treatment but conclusion may depend on the parameters (m_q, wave function)

Coalescence according to extended Dover framework

(PRC 79 044906)

$$N_\Phi = \int \frac{d^3 p_q}{(2\pi\hbar)^3 E_q} \frac{p_q \cdot d\hat{\sigma}}{u_Q \cdot d\hat{\sigma}} f_q(x_Q, p_q)(\sqrt{2\pi} R_c)^3 \times F_\Phi(p_Q, p_q),$$

Elastic for leptons @ RHIC



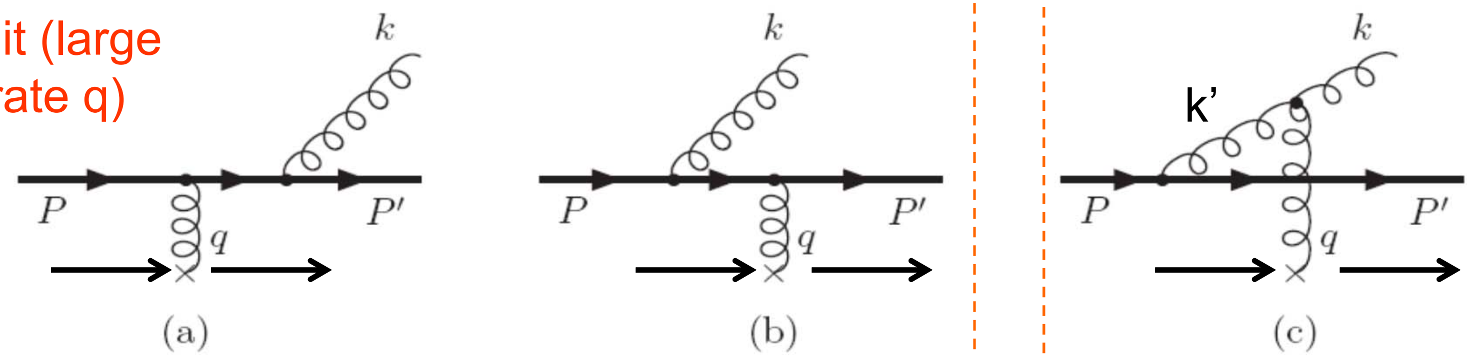
In principle:
Need for
radiative
energy loss…

Good agreement for NPSE as well

Induced Energy Loss

Generalized Gunion-Bertsch (NO COHERENCE) for finite HQ mass, dynamical light partons

Eikonal limit (large E, moderate q)



Dominates as small x as one “just” has to scatter off the virtual gluon k’

$$\omega \frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2 k_\perp dq_\perp^2} = \frac{N_c \alpha_s}{\pi^2}(1-x) \times \frac{J_{\rm QCD}^2}{\omega^2} \boxed{\times \frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

with

$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2 + x^2 M^2 + (1-x)\underbrace{m_g^2}} - \frac{\vec{k}_\perp - \vec{q}_\perp}{\left(\vec{k}_\perp - \vec{q}_\perp\right)^2 + x^2 \underbrace{M^2} + (1-x) m_g^2} \right)^2$$

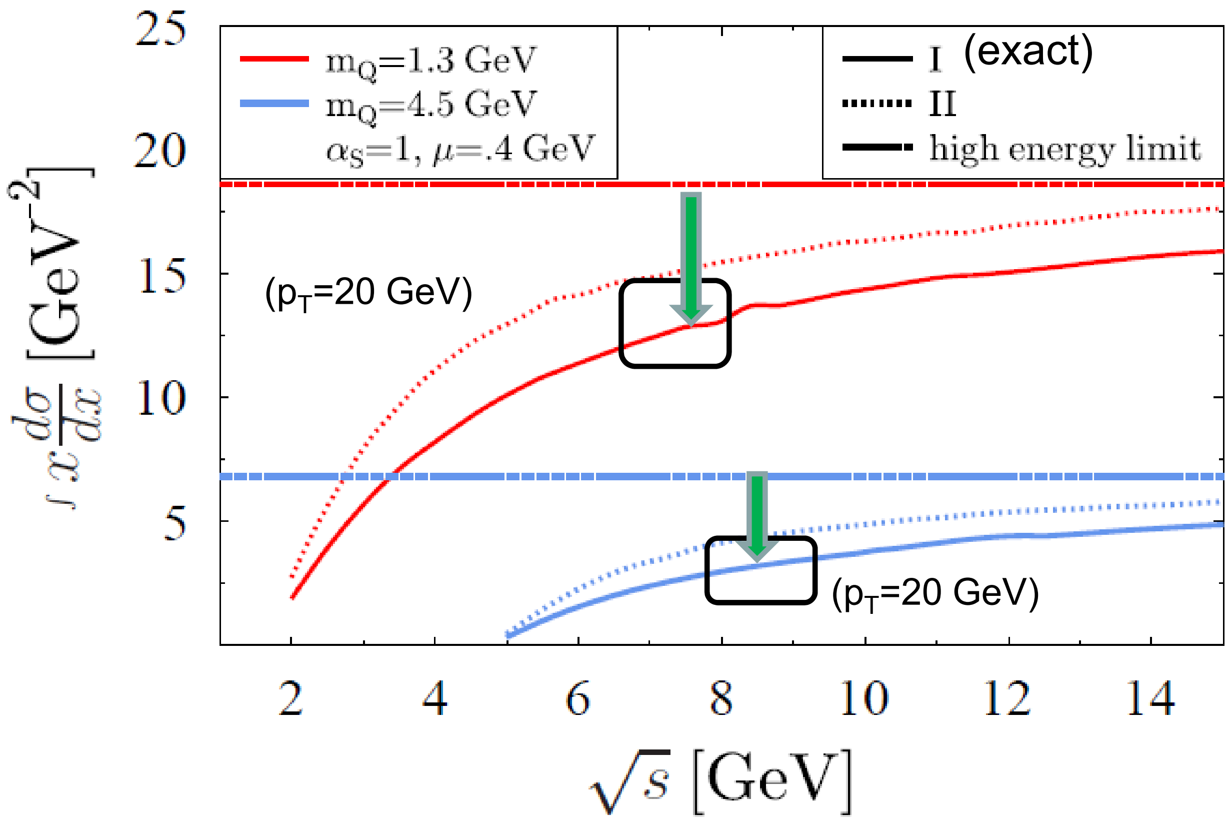
Gluon thermal mass ~2T (phenomenological; not in BDMPS)

Quark mass

Both cures the collinear divergences and influence the radiation spectra (dead cone effect)

Incoherent Induced Energy Loss

… & finite energy !



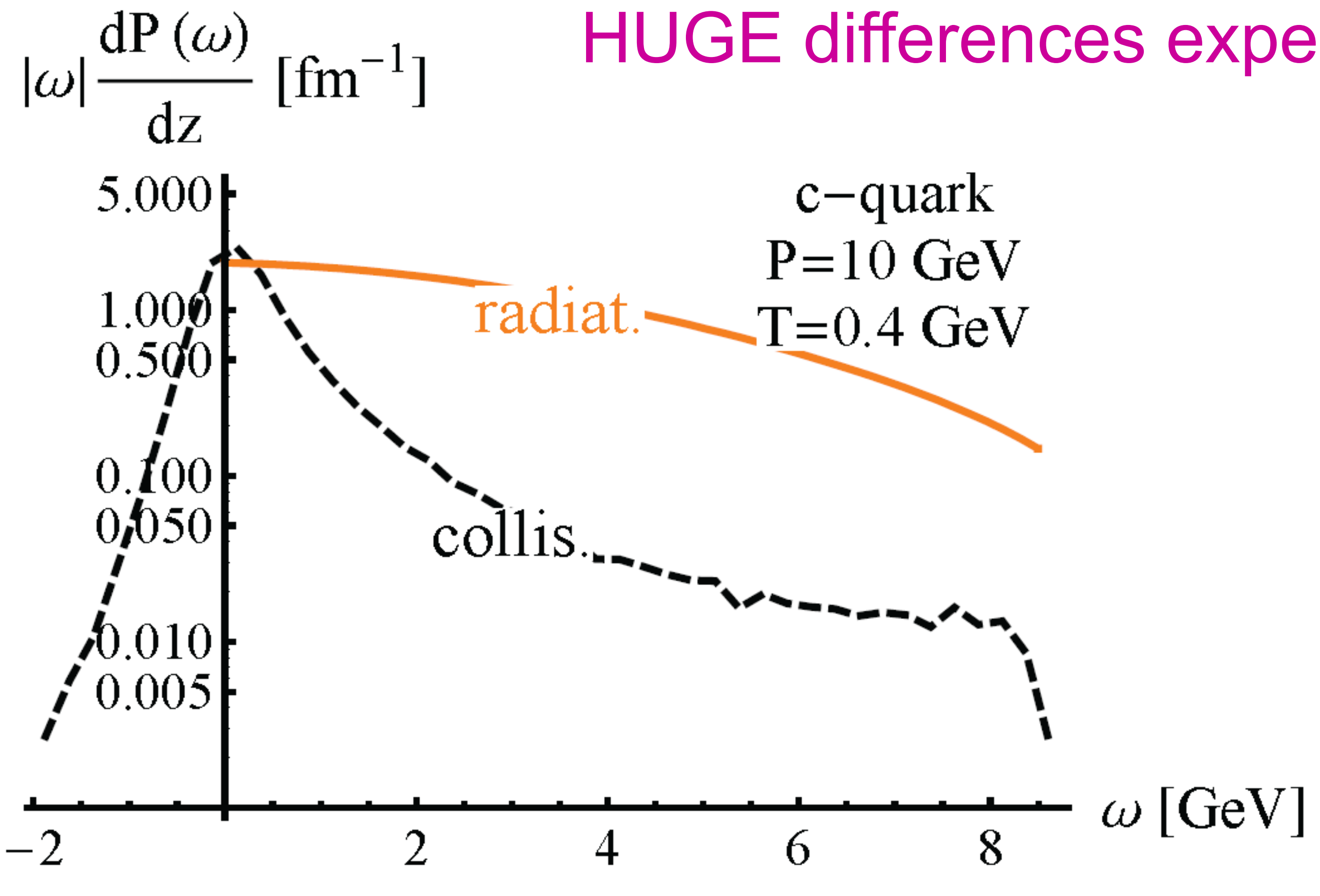
Gousset, Gossiaux & Aichelin, Phys. Rev. D 89, 074018 (2014)

Finite energy lead to strong reduction of the radiative energy loss at intermediate p_T

Incoherent Induced Energy Loss

Probability P of energy loss ω per unit length (T,M,…):

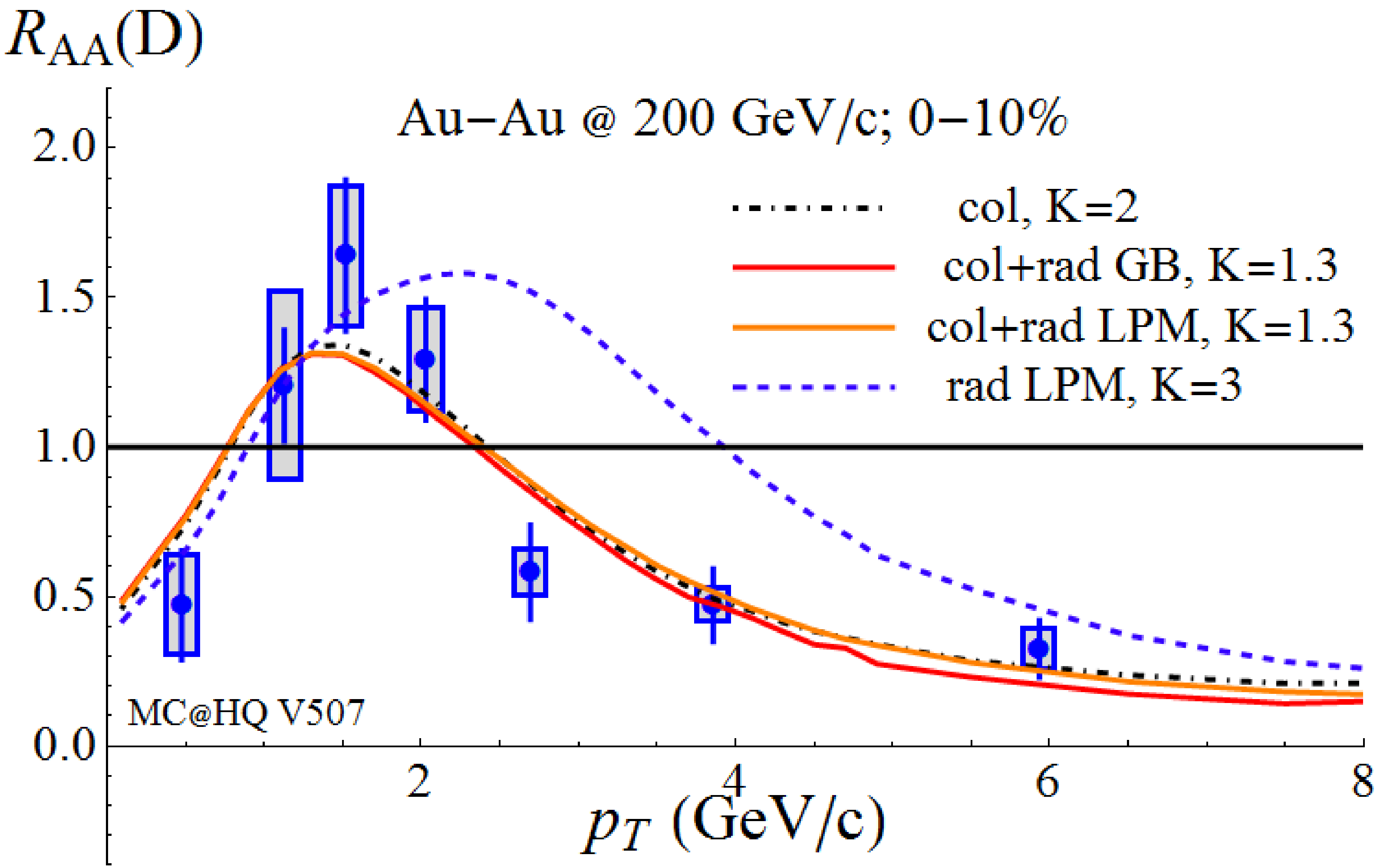
HUGE differences expected



Caveat: no detailed balance implemented yet

{Radiative + Elastic} vs Elastic for D mesons @ RHIC

=> Allow for some global rescaling of the rates: “K” fixed on experiment



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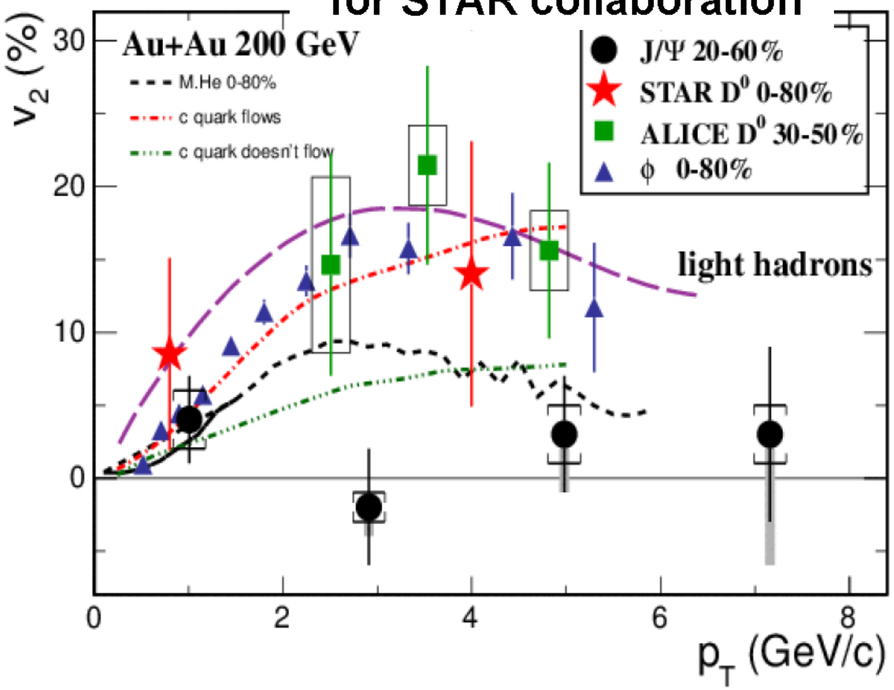

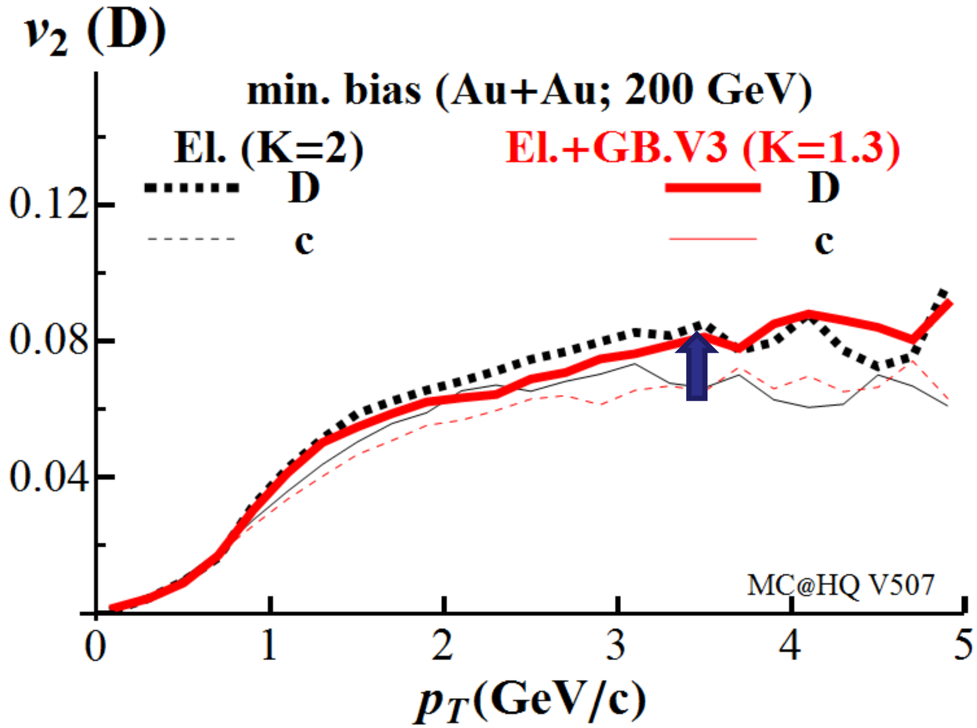

No lack of elliptic flow wrt pure elastic processes

Coalescence according to extended Dover framework

(PRC 79 044906)

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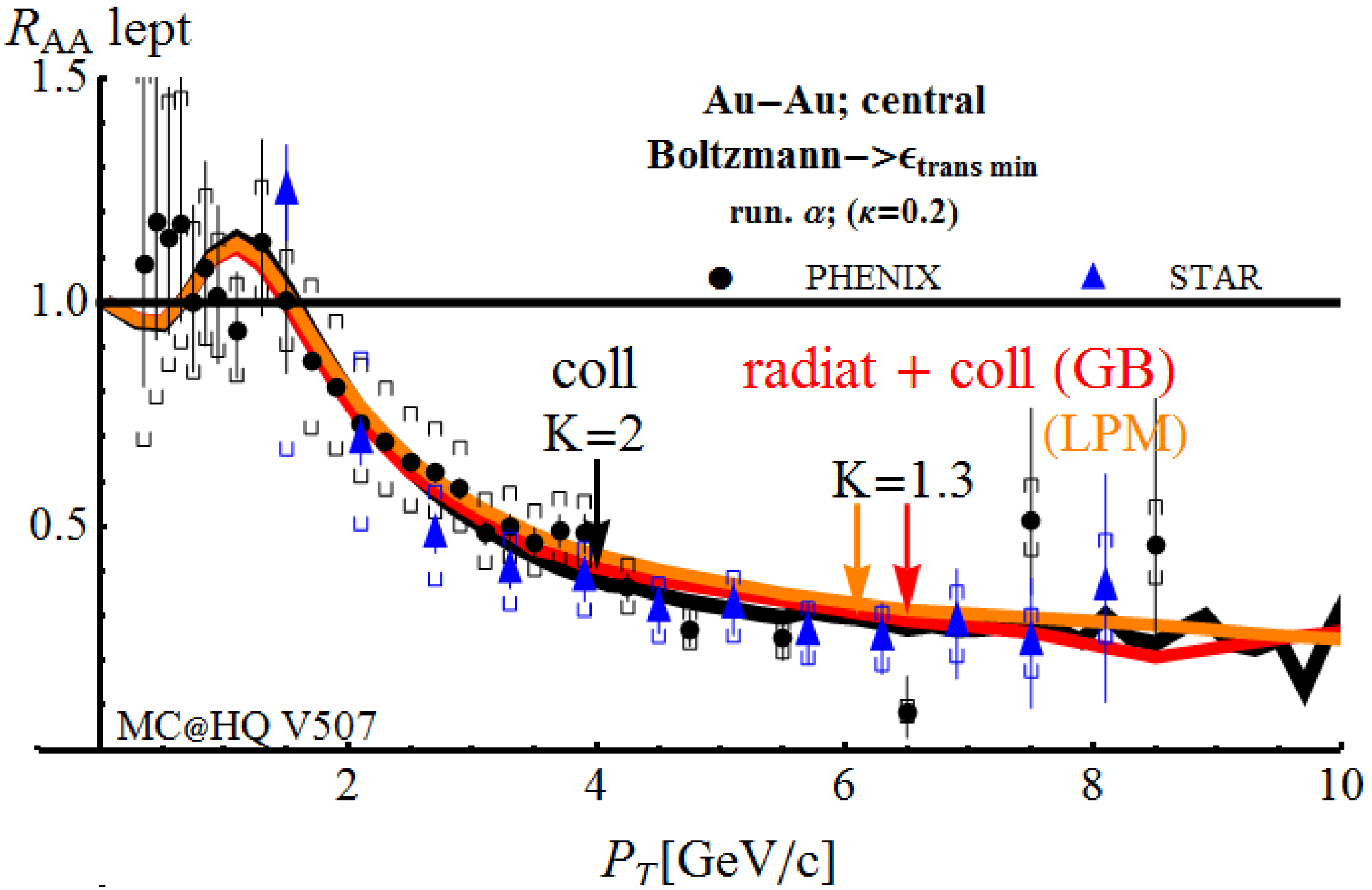
{Radiative + Elastic} vs Elastic for leptons @ RHIC



Good agreement for NPSE as well

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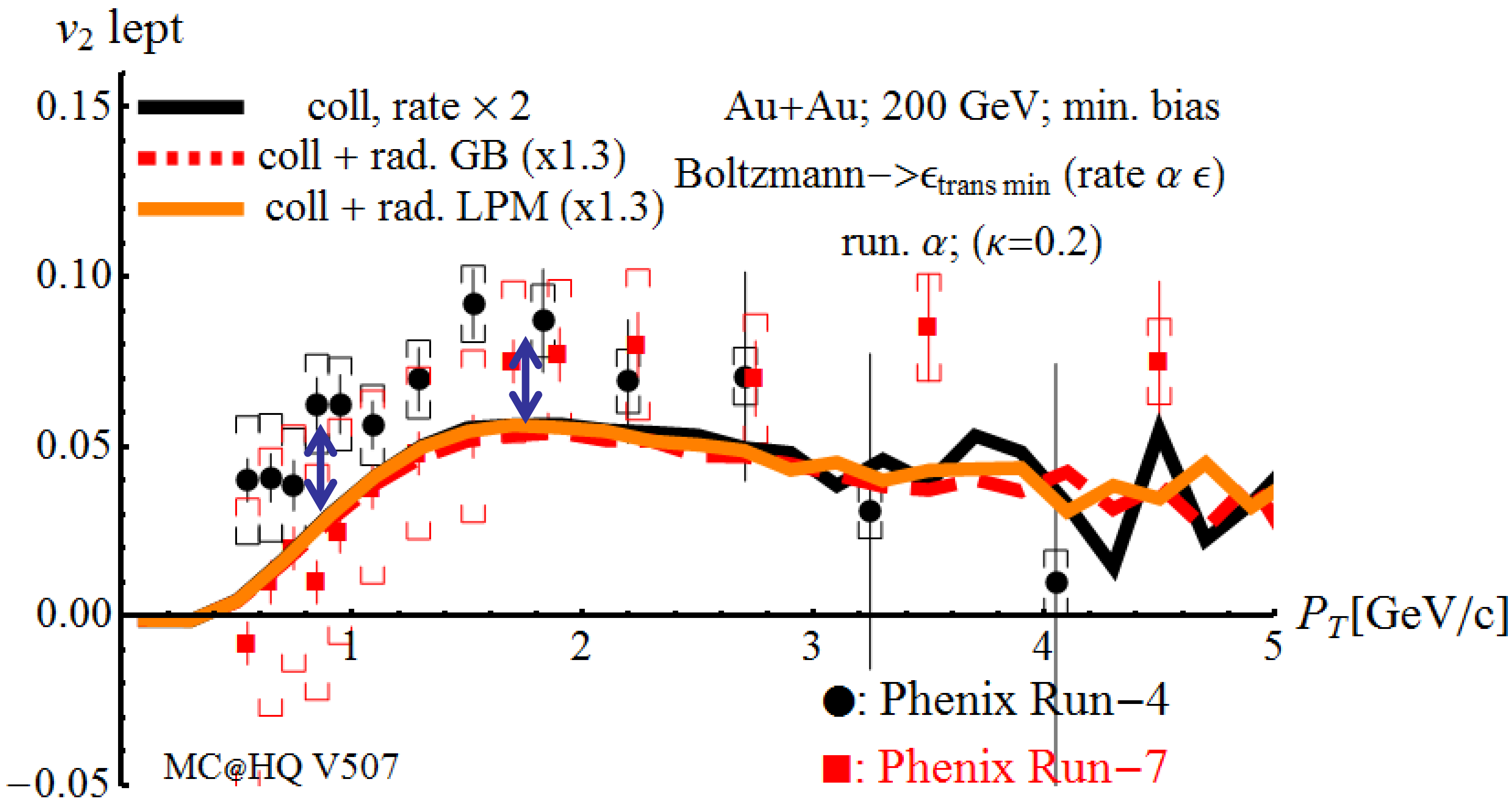


Good agreement for NPSE as well

“Early” Conclusions from RHIC

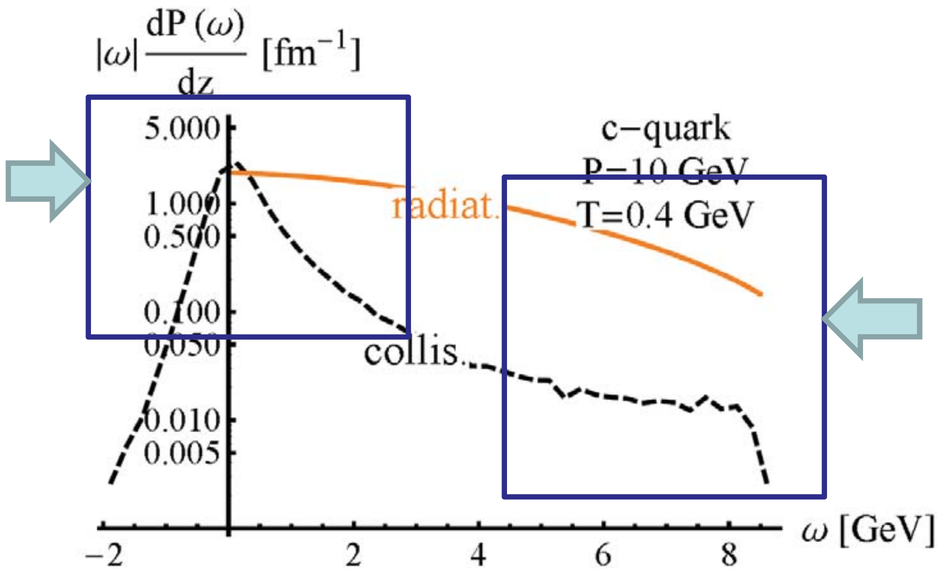
➢ Good consistency between NPSE and D mesons (10% difference in K values)…

➢… within a model with mass hierarchy

➢ ΔE radiative < ΔE elastic

➢ Present data at RHIC cannot decipher between the 2 local microscopic E-loss models (elastic, elastic + radiative GB) ⇒ Not sensitive to the large-ω tail of the Energy-loss probability (thanks to initial HQ p_T-distribution)

“Fokker Planck” regime

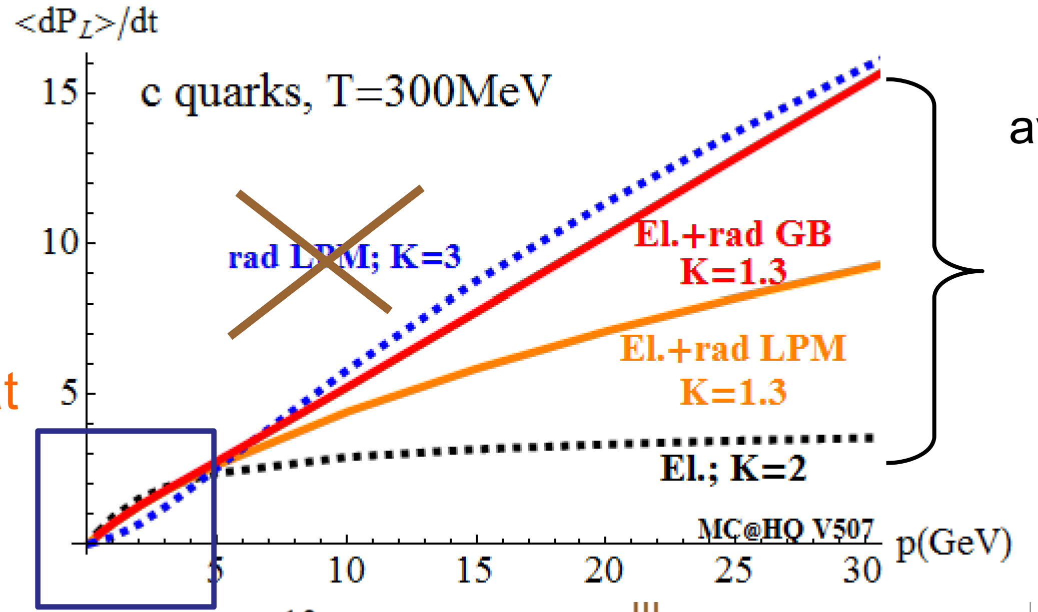


“hard scattering” regime

QGP properties from HQ probe at RHIC (why do we care ?)

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:

Similar diffusion coefficient at low p



the drag coefficient reflects the average momentum loss (per unit time) => large weight on $x \sim 1$

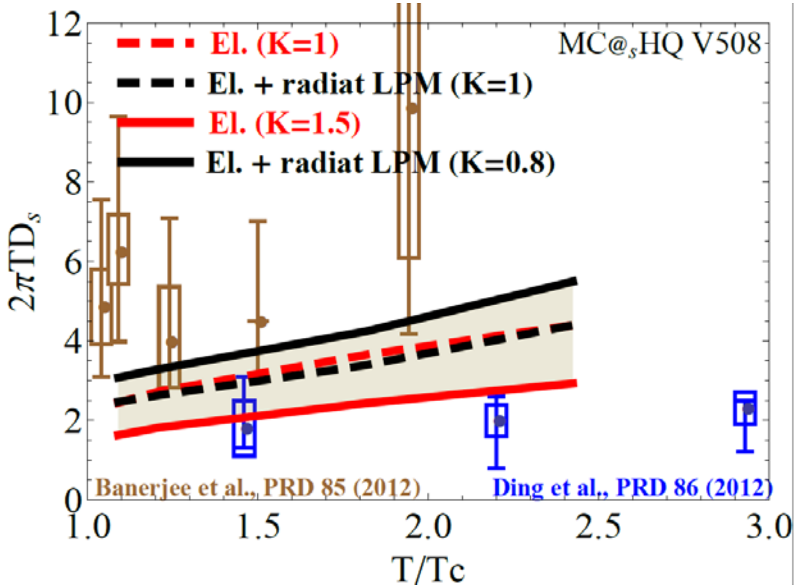
Present RHIC experiments cannot resolve between those various trends

Hope that LHC can do !!!

We extract it from data

(starting from SQM 2008)

We compare with recent lattice results

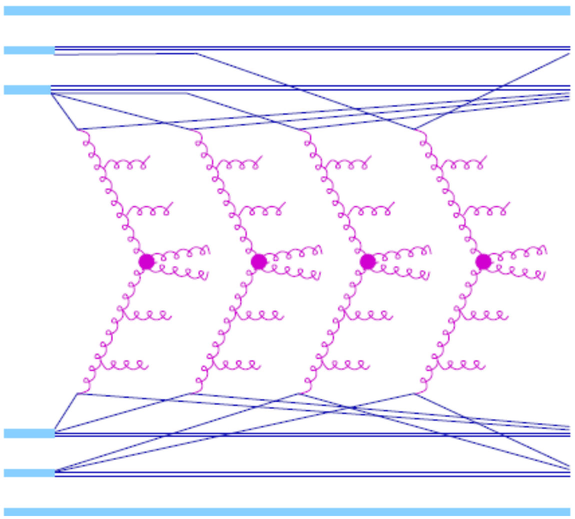


Main message

It is possible to reveal some fundamental property of QGP using HQ probes

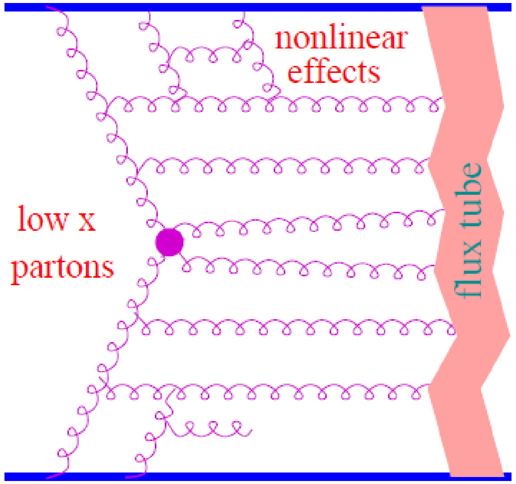
Going LHC: EPOS2 + Hydro as a background for MC@sHQ

EPOS + Hydro : state of the art framework that encompass pp, pA and AA collisions



EPOS (initial conditions):

- Model based on Gribov-Regge multiple pomeron interactions
- Particle production in cut (semi-hard) pomerons, seen as partons ladder
- Soft particles form a flux tube (string, with its own dynamics, incl. string breaking)… lots of them in A-A
- Slow string segments, far from the surface, are mapped to fluid dynamic fields (-> hydro)
- Hard particles -> jets

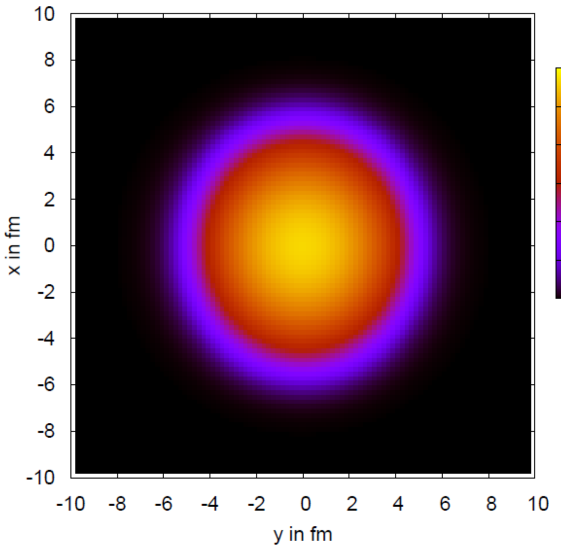


Ref: K. Werner, Iu. Karpenko, M. Bleicher, T. Pierog, and S. Porteboeuf-Houssais Phys. Rev. C 85 (2012), 064907

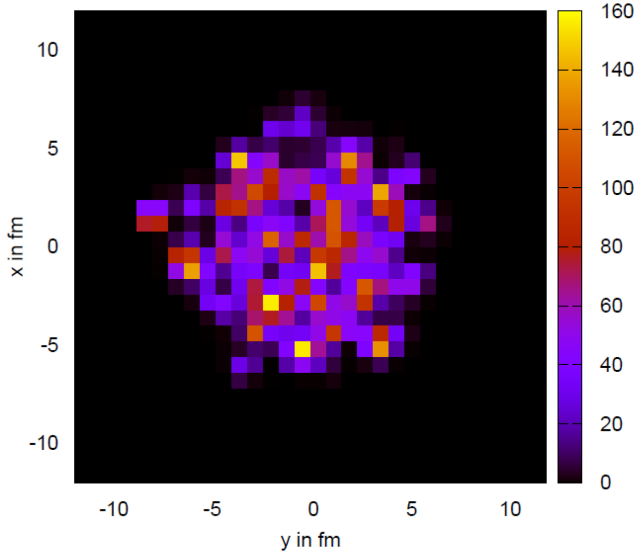
Going LHC: EPOS2 as a background for MC@sHQ

EPOS: state of the art framework that encompass pp, pA and AA collisions

Initial energy density



Kolb Heinz (used previously)



EPOS

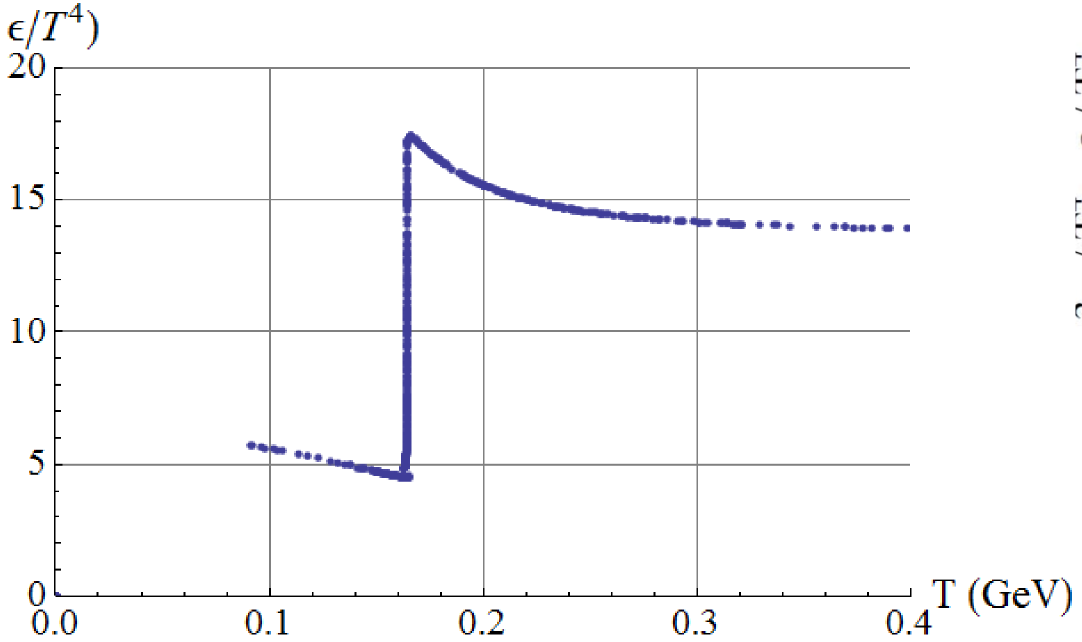
Beware: ≠ color scales

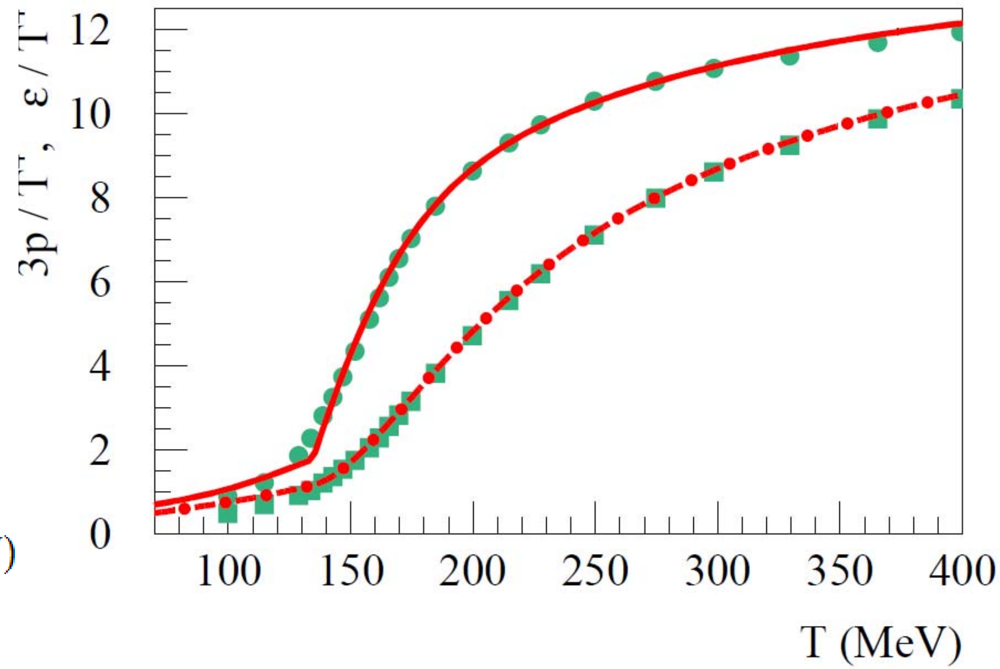
More realistic hydro and initial conditions => original HQ studies such as:

1) fluctuations in HQ observables (some HQ might « leak » through the « holes » in the QGP)

2) correlations between HF and light hadrons

Large differences in the EOS !

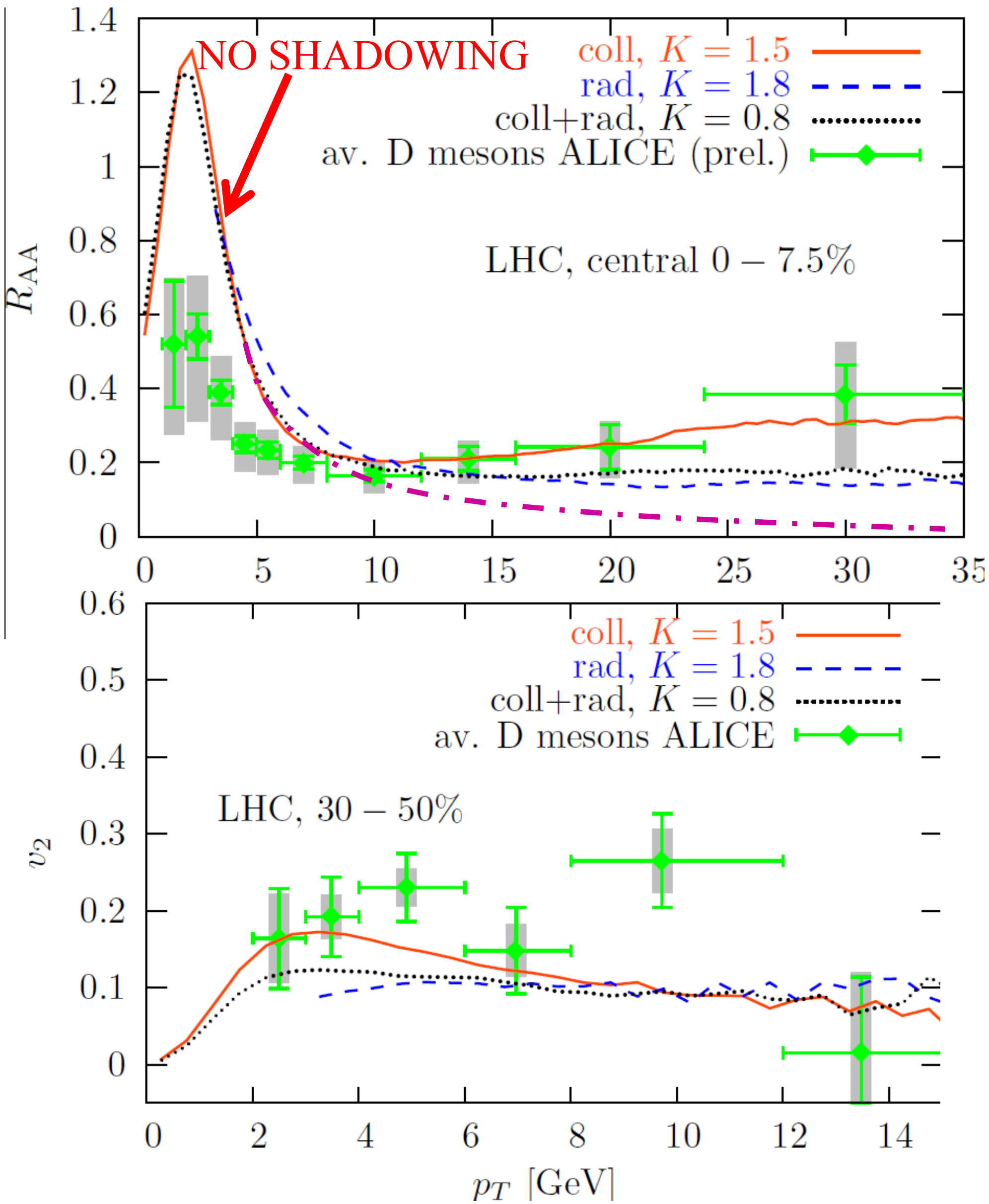




Kolb Heinz: bag model (1rst order transition btwn hadronic phase and massless partons)

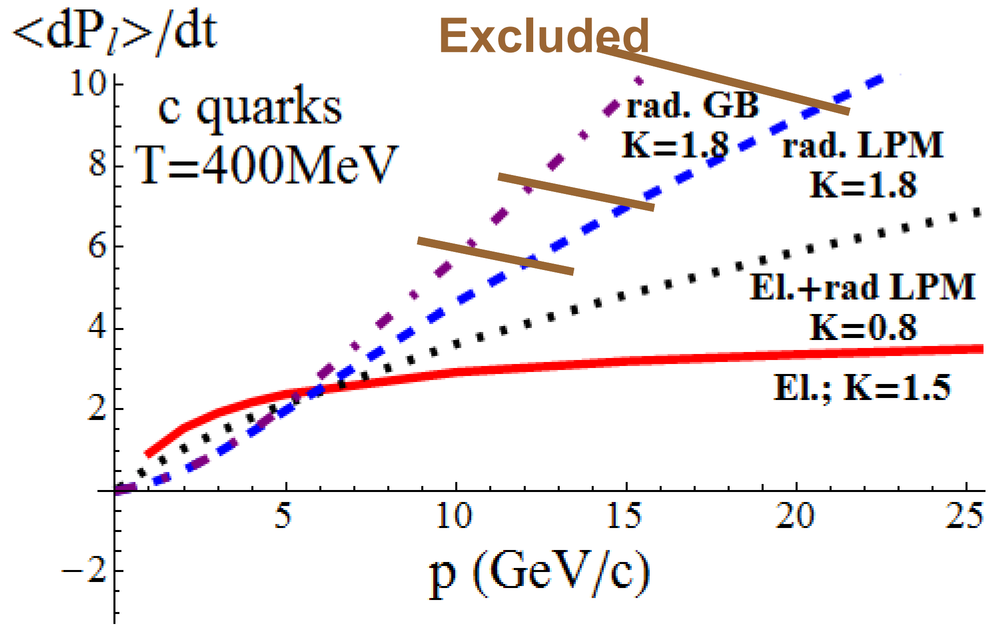
EPOS2: fitted on the lattice data from the Wuppertal-Budapest collaboration: cross-over

Going LHC: EPOS2 as a background for MC@sHQ



Same microscopic ingredients as for RHIC (ΔE α L);

N.B.: K values: slightly smaller then what obtained from RHIC

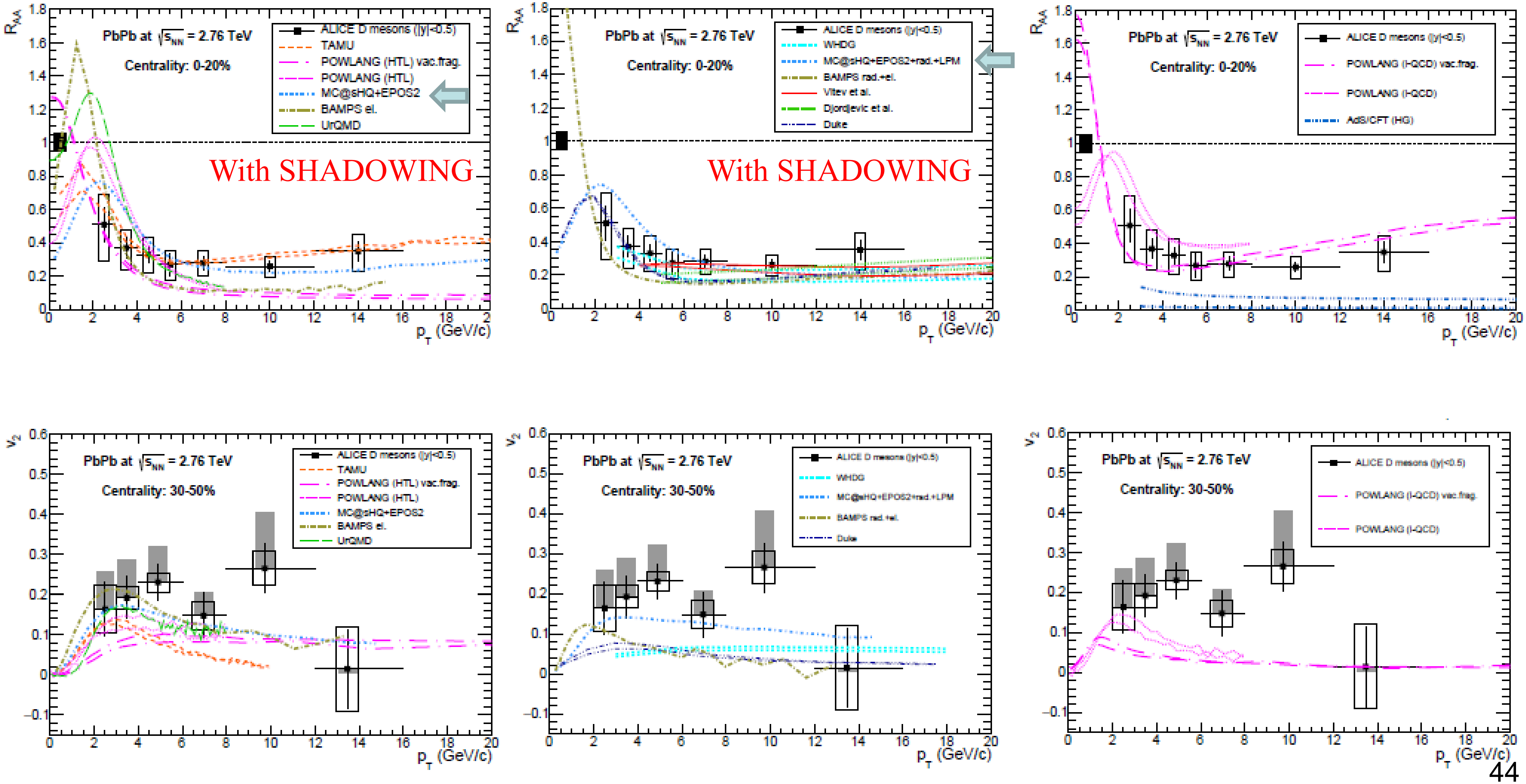


Data at large p_T seems to favor « Collisional only »- like average momentum loss

Further comparison with model calculations at LHC

Sapore Gravis report (arxiv 1506.03981)

Elastic | **(Elastic +) Radiative** | **Other**

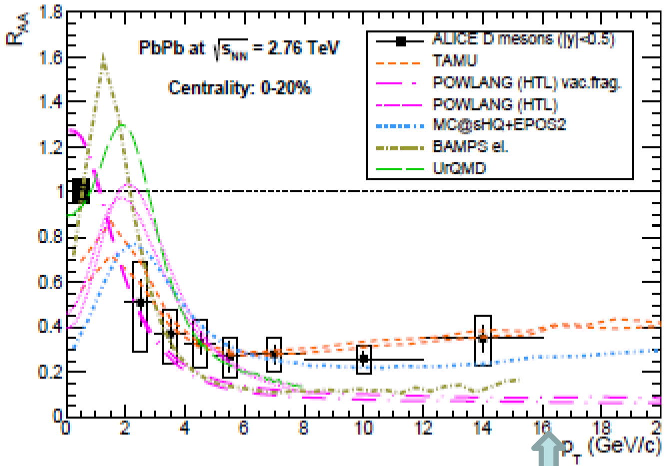


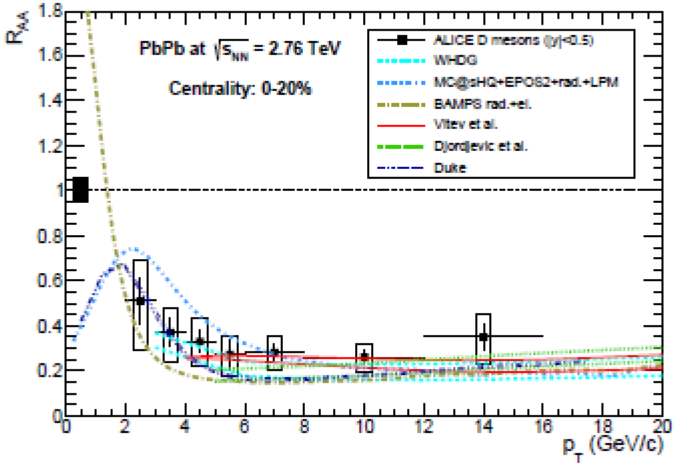
Further comparison with model calculations at LHC

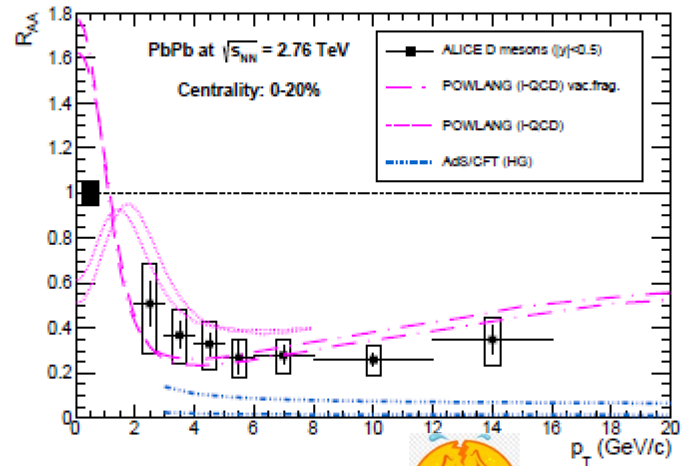
Far from reaching a global understanding

Sapore Gravis report (arxiv 1506.03981)

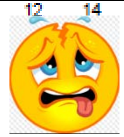
Elastic | **(Elastic +) Radiative** | **Other**

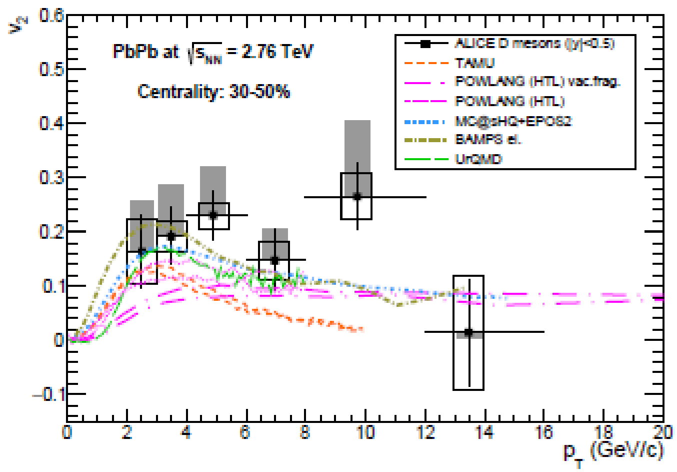


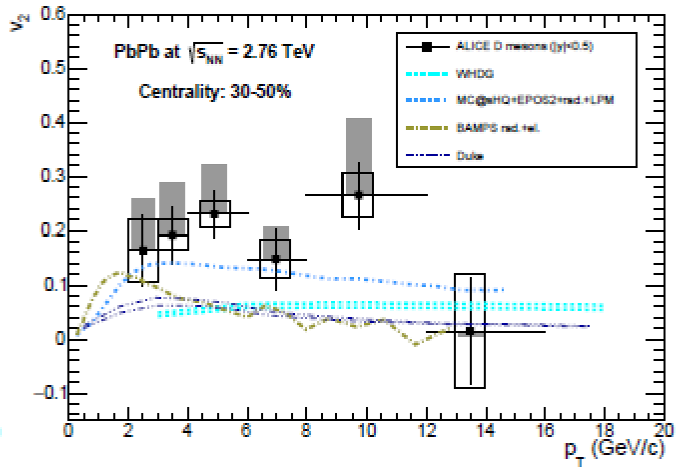


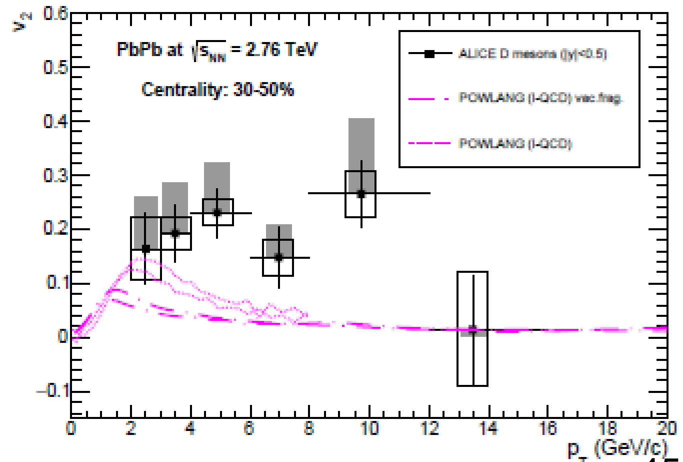


f.i.: largest quenching with the weakest model (in principle)



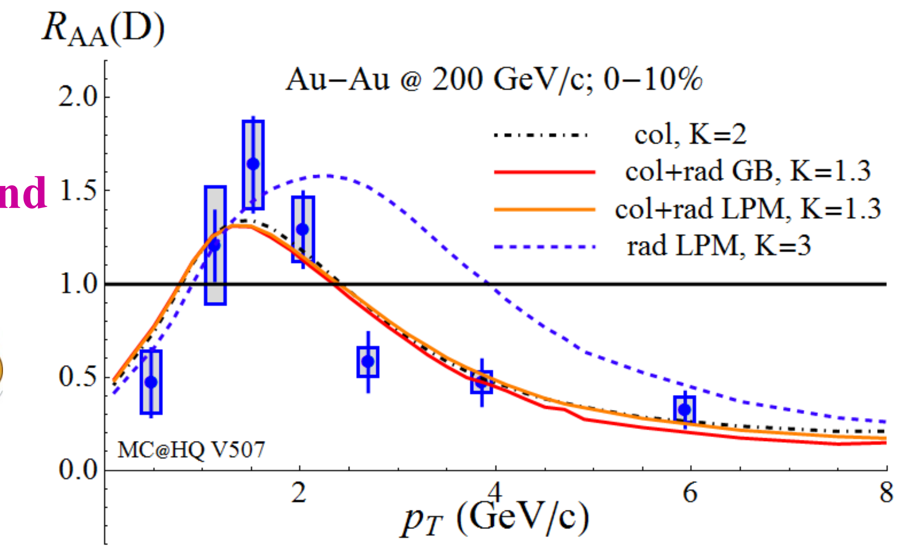


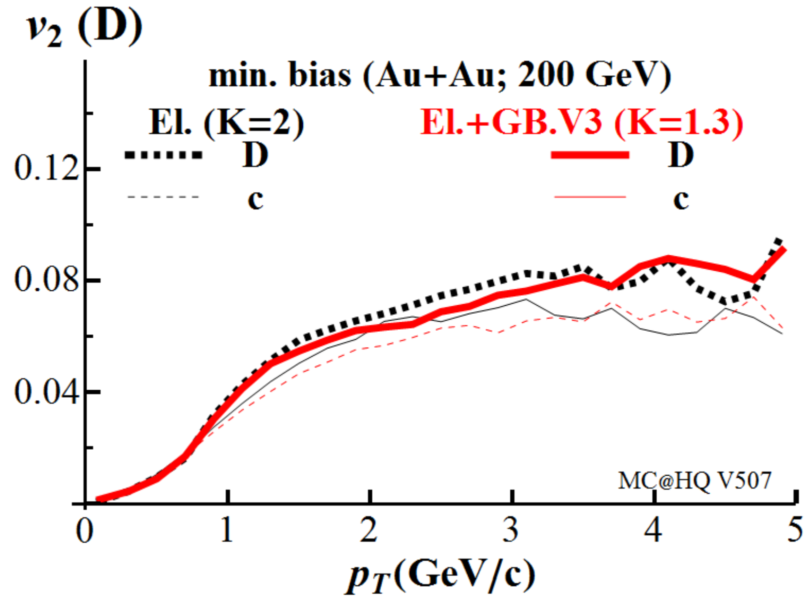




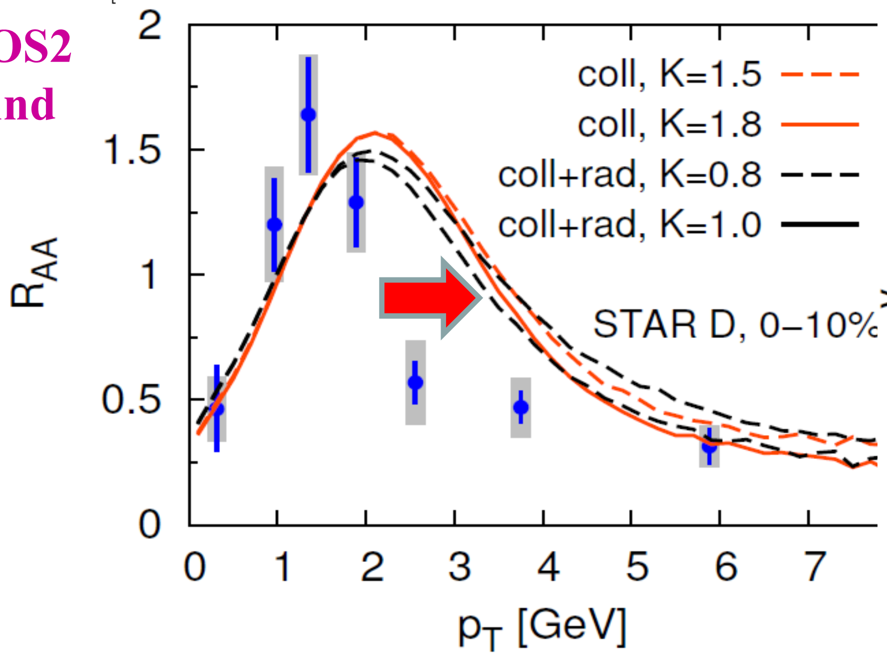
Back to RHIC: EPOS 2 as a background

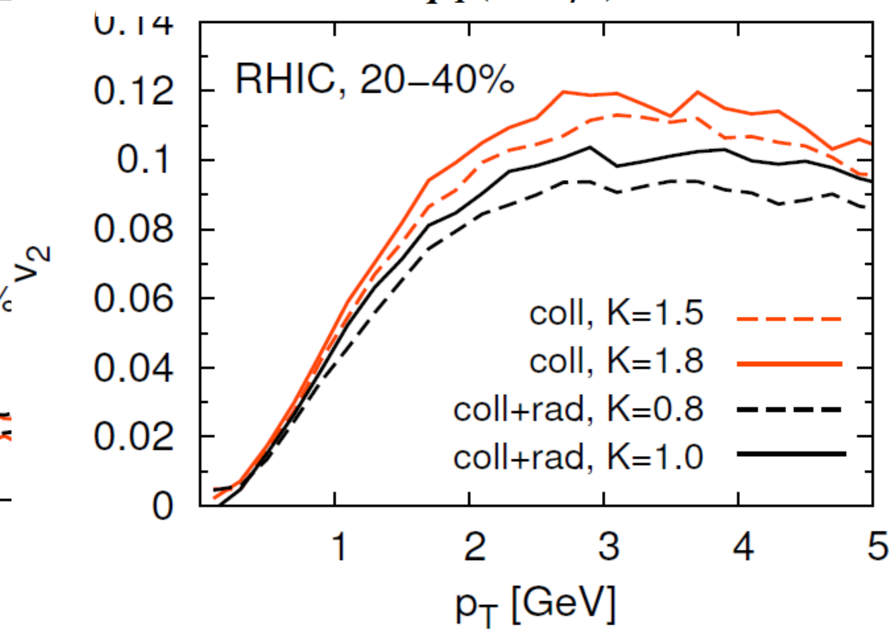
With KH background



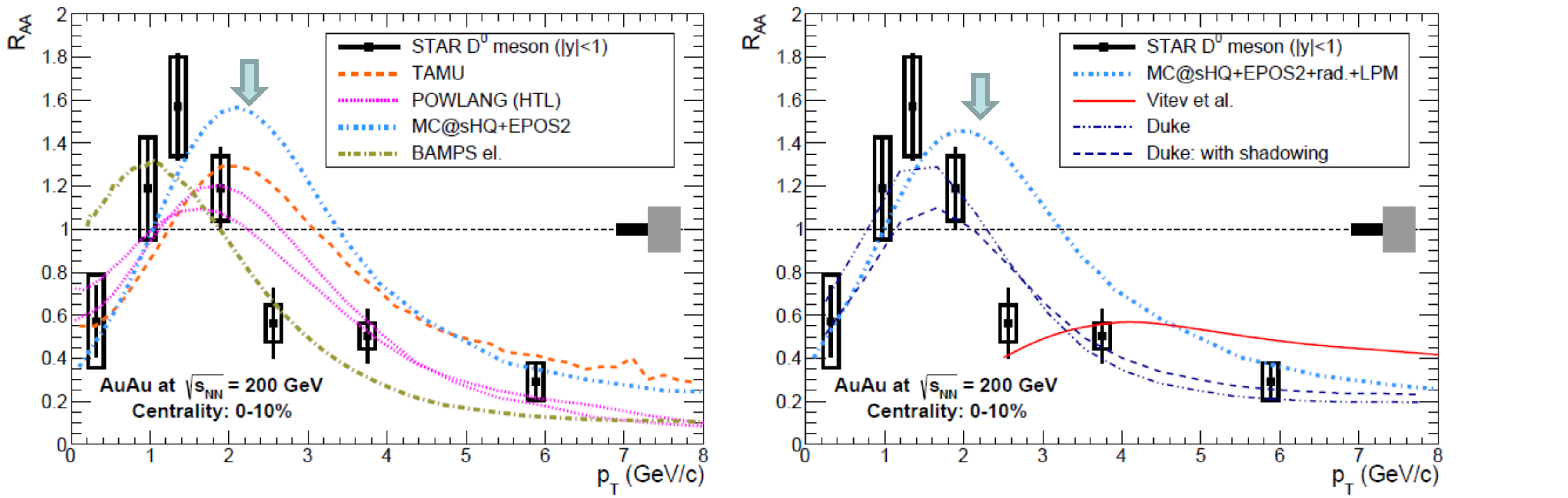


With EPOS2 background





Back to RHIC: EPOS 2 as a background



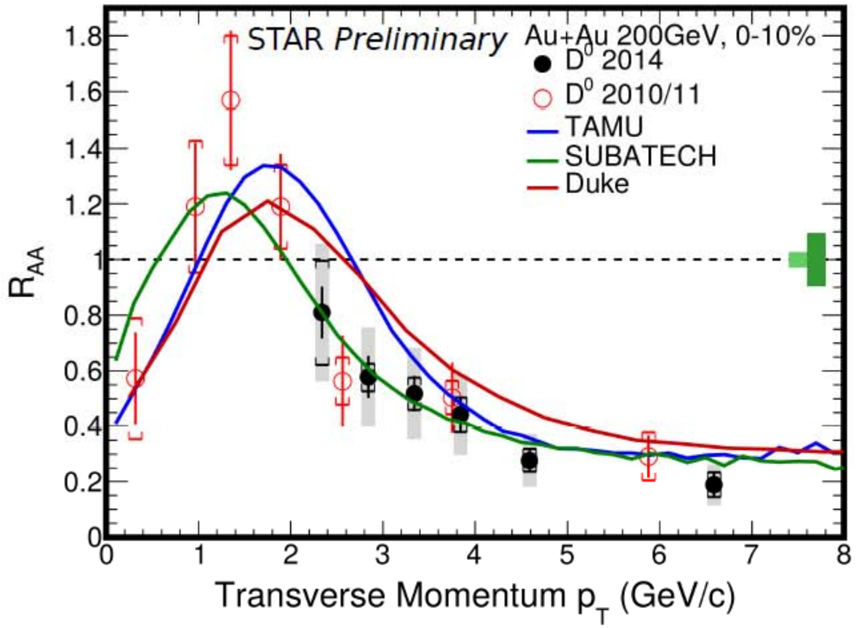
June 2015

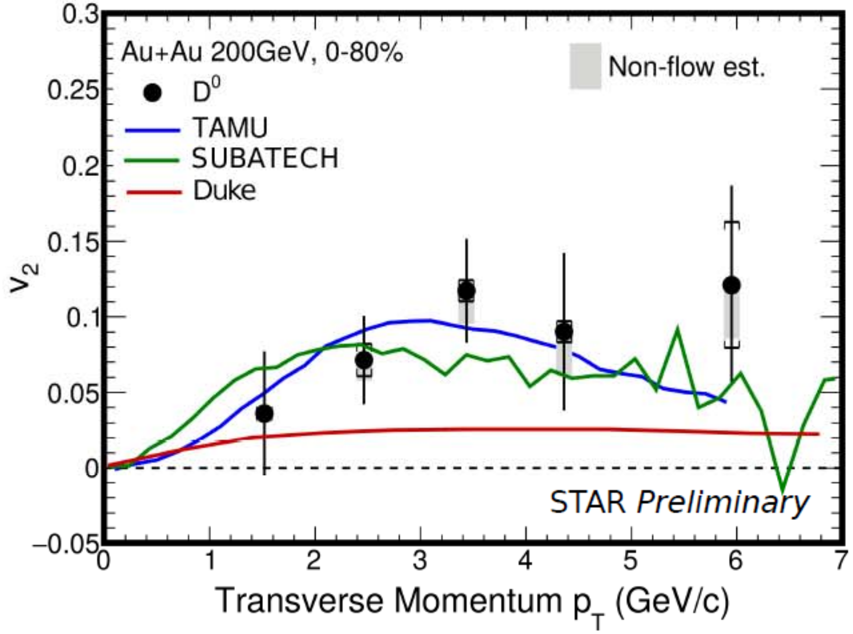
N.B.: light particle spectra do not seem to show such large deviations btwn the 2 background models

Back to RHIC: EPOS 3 as a background

Comparison to Theory

Sept 2015





	D × 2πT	Diff. Calculation
TAMU	2-11	T-Matrix
SUBATECH	2-4	pQCD+HTL
Duke	7	Free parameter

arXiv:1506.03981 (2015) & private comm.

- Data favors models with charm diffusion
  → charm exhibits collectivity with the medium

Subatech: same Eloss model as previously

STAR ☆

Mustafa Mustafa - QM15 - Kobe, Japan

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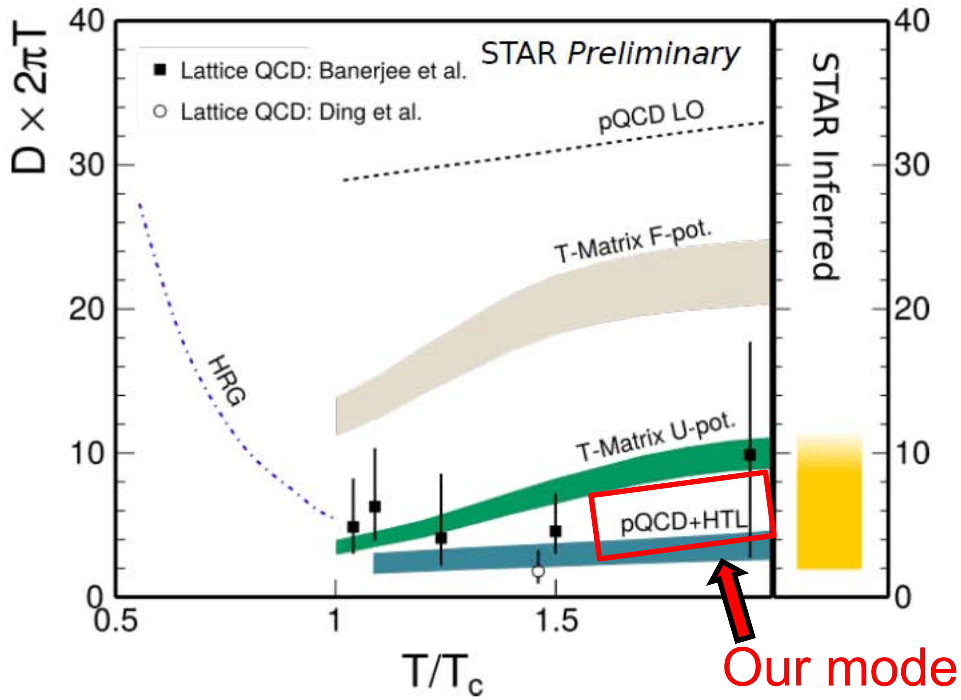
Back to RHIC: EPOS 3 as a background

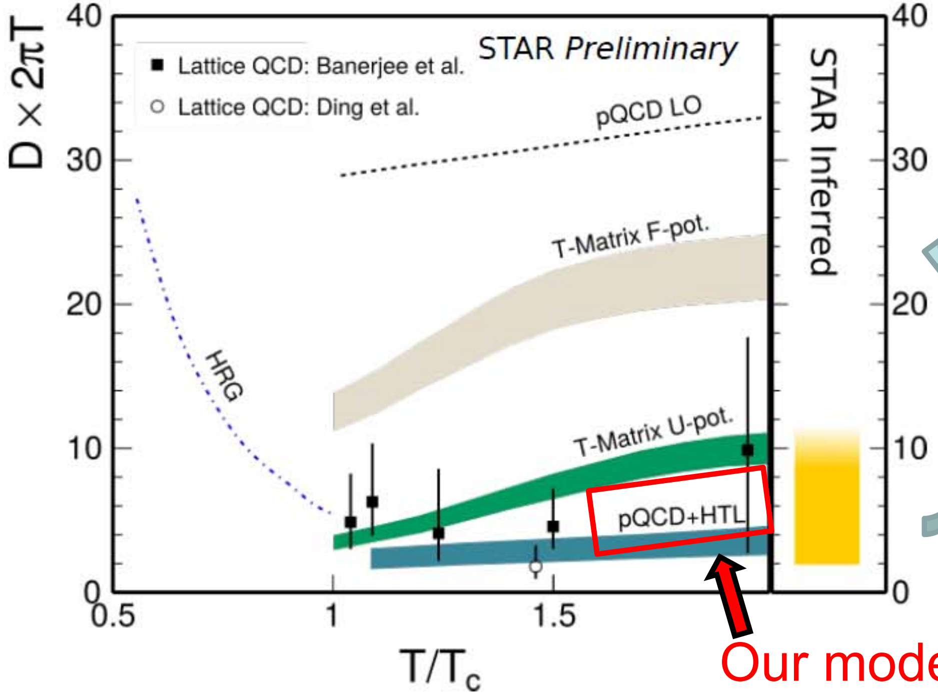
Comparison to Theory II – Charm Diffusion Coefficient



- Models with charm diffusion coefficient of 2 - ~10 describe STAR R_{AA} and v_2 data
- Lattice calculations are consistent with values inferred from data

Back to RHIC: EPOS 3 as a background

Comparison to Theory II – Charm Diffusion Coefficient



But how does it compare with the "our force is close to the one obtained with the free energy taken as a potential" statement made above ?

Our model ? Not pQCD

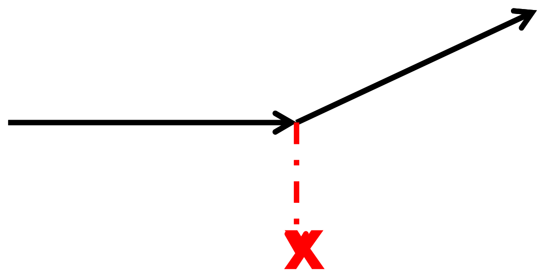
- Models with charm diffusion coefficient of 2 - ~10 describe STAR R_{AA} and v_2 data
- Lattice calculations are consistent with values inferred from data

Refined observables

Central question (to better understand the probe):

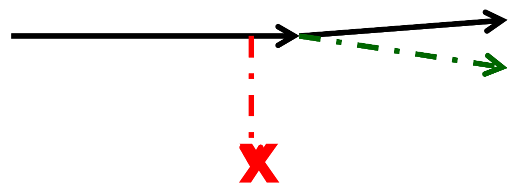
How to distinguish between

Typical - Collisional



Large cross-section,
moderate E-loss per collision
large angular deflection
Mass comes as a scale in a log

Typical - Radiative



Small cross-section,
large E-loss per collision
small angular deflection
Mass regularizes collinear divergence
=> stronger mass-influence

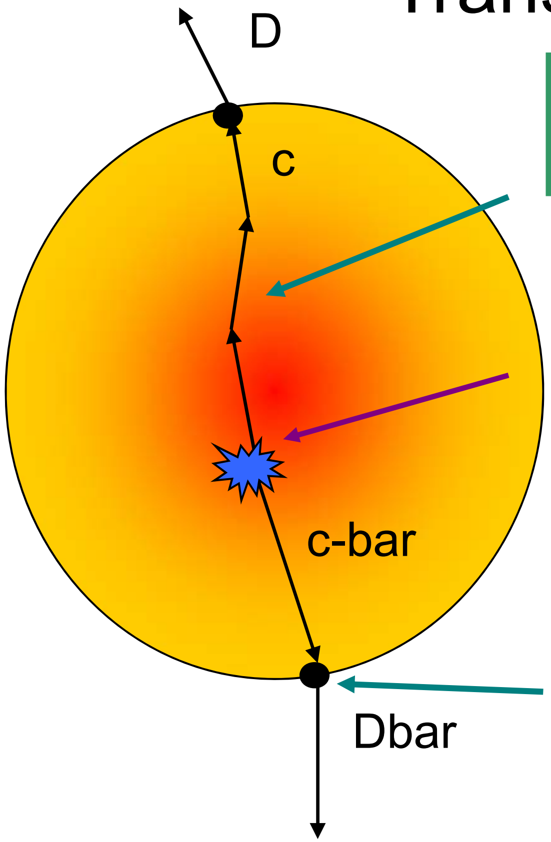
Distinguishing btwn the models: angular correlations…

2-body observables

Large cross-section,
moderate E-loss per collision
large angular deflection,

Small cross-section,
large E-loss per collision
small angular deflection,

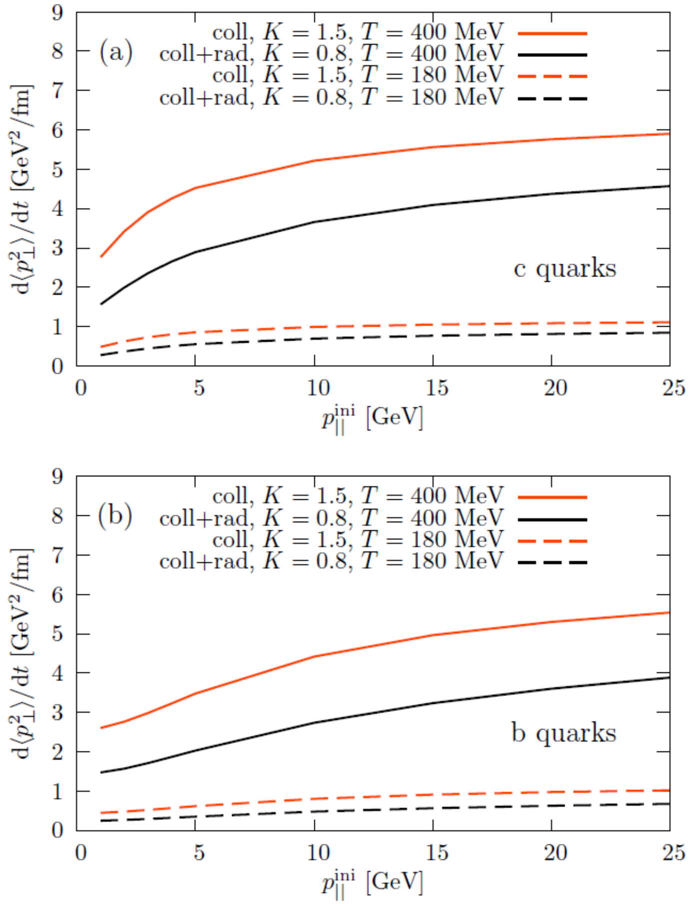
Transverse plane



Transverse broadenning ./. Initial direction

Initial correlation ; back to back at leading order

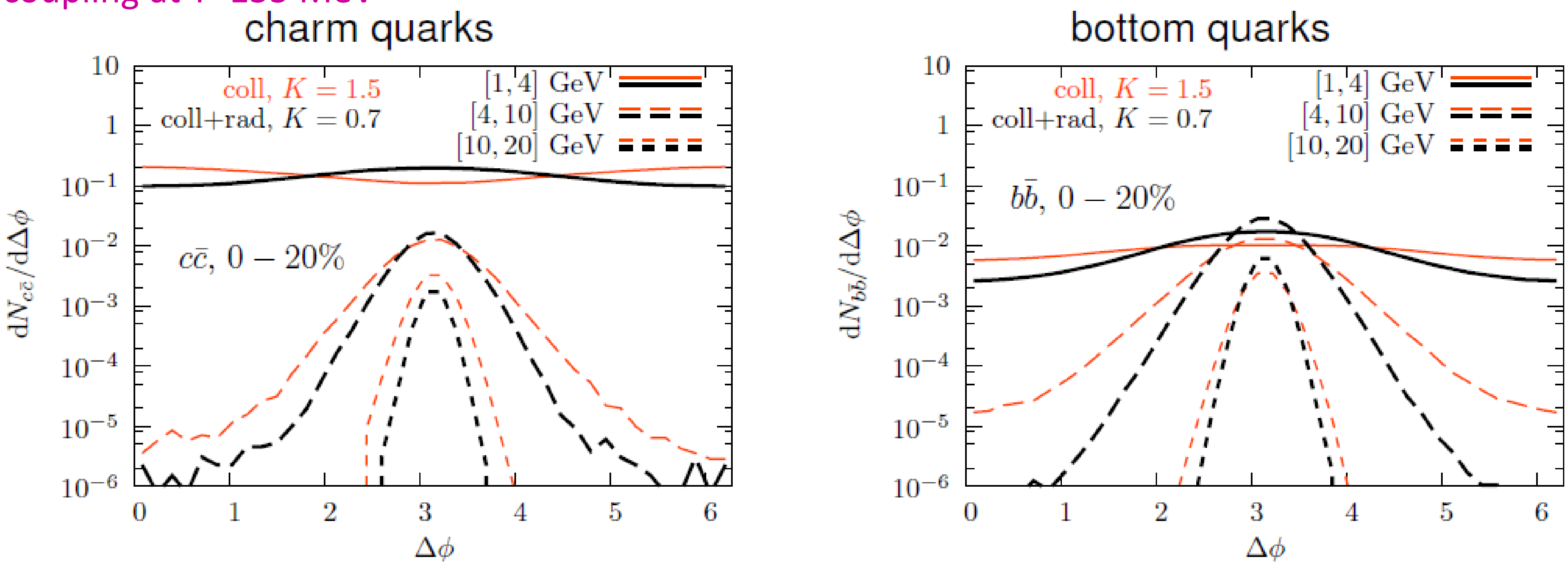
Effect of hadronization on angular correlation ?



Nahrgang et al Phys. Rev. C 90, 024907 (2014)

Heavy quarks azimuthal correlations: Back-to-back

Pb-Pb at LHC, HQ initialized back-to-back, no background from uncorrelated pairs, eff.deg=1; decoupling at T=155 MeV



- Stronger broadening in a purely collisional than in a **collisional+radiative** interaction mechanim
- At low pT, initial correlations are almost washed out. Some collectivity seen in the purely collisional scenario
- Variances in the intermediate pT range (4 GeV-10 GeV): 0.18 vs **0.094** (charm) and 0.28 vs **0.12** (bottom)
- At higher pT, initial correlations survive the propagation in the medium

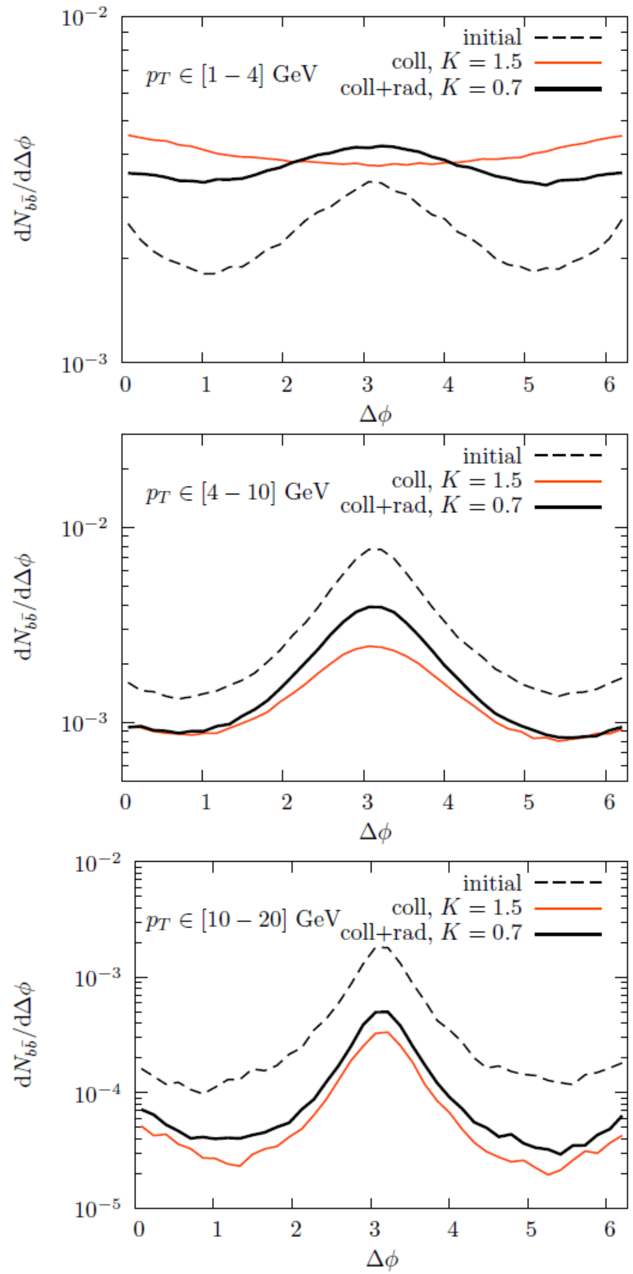
Nahrgang et al Phys. Rev. C 90, 024907 (2014)

… and with Realistic initial distributions: MC@NLO

Next-to-leading order QCD matrix elements coupled to parton shower (HERWIG) evolution: MC@NLO

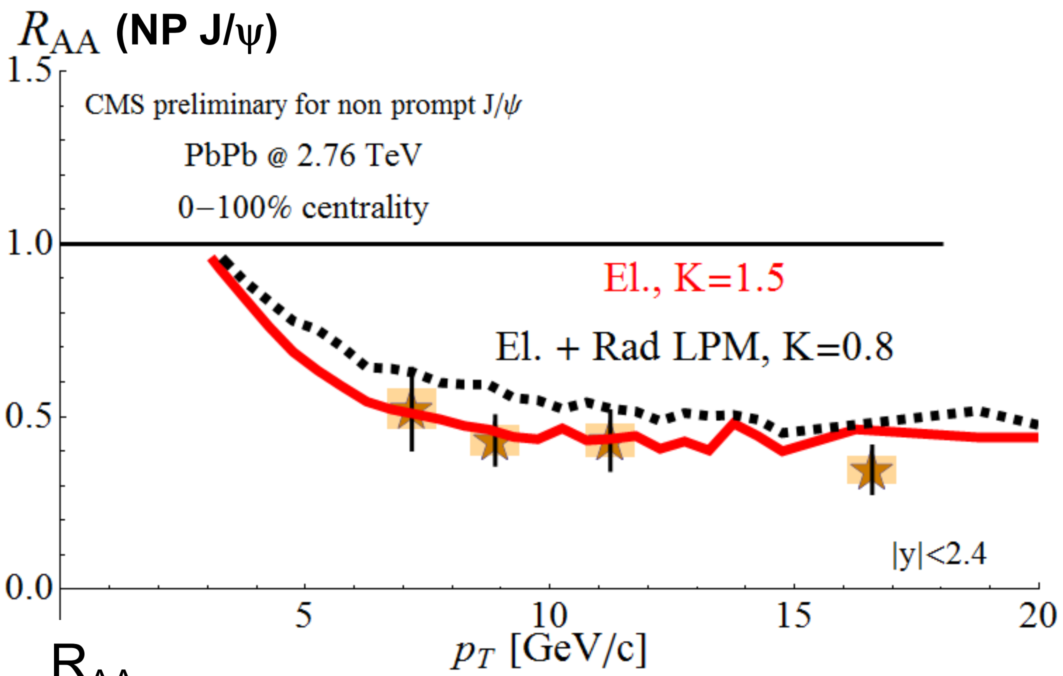
S. Frixione and B. R. Webber, JHEP **0206** (2002)
S. Frixione, P. Nason and B. R. Webber, JHEP **0308** (2003)

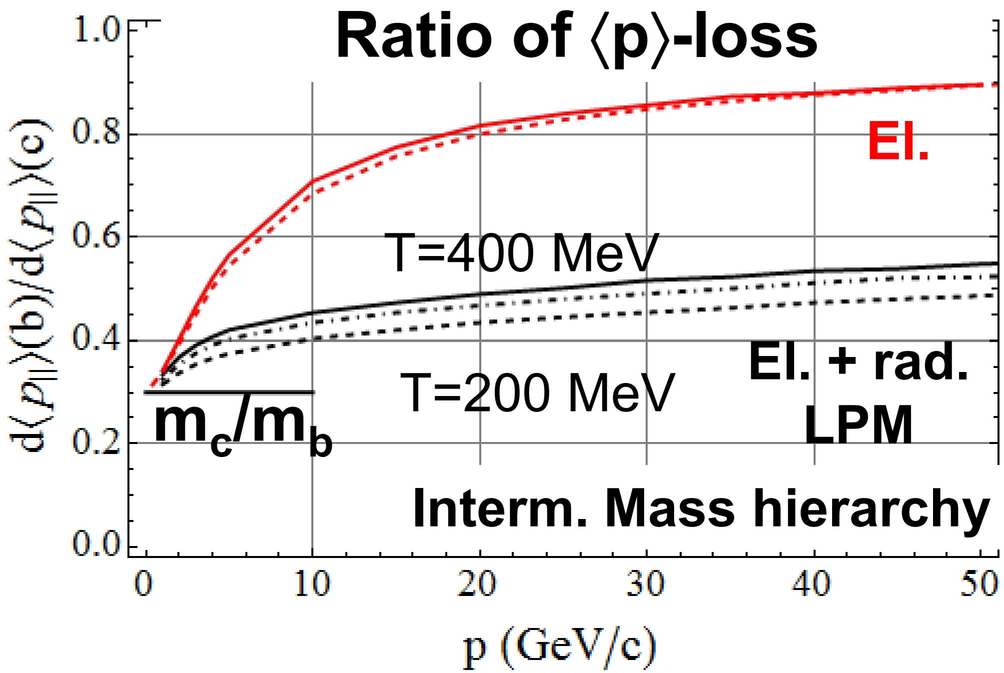
- Gluon splitting processes lead to an initial enhancement of the correlations at $\Delta\phi \approx 0$.
- For intermediate pT : increase of the variances from 0.43 (initial NLO) to 0.51 (≈ 20%) for the purely collisional mechanisms and to 0.47 (≈ 10%) for the interaction including **radiative** corrections (no additivity with initial width).
- At larger pT, the deviations from back to back correlations are mostly due to initial NLO corrections.
- Different NLO+parton shower approaches agree on bottom quark production, differences remain for charm quark production!

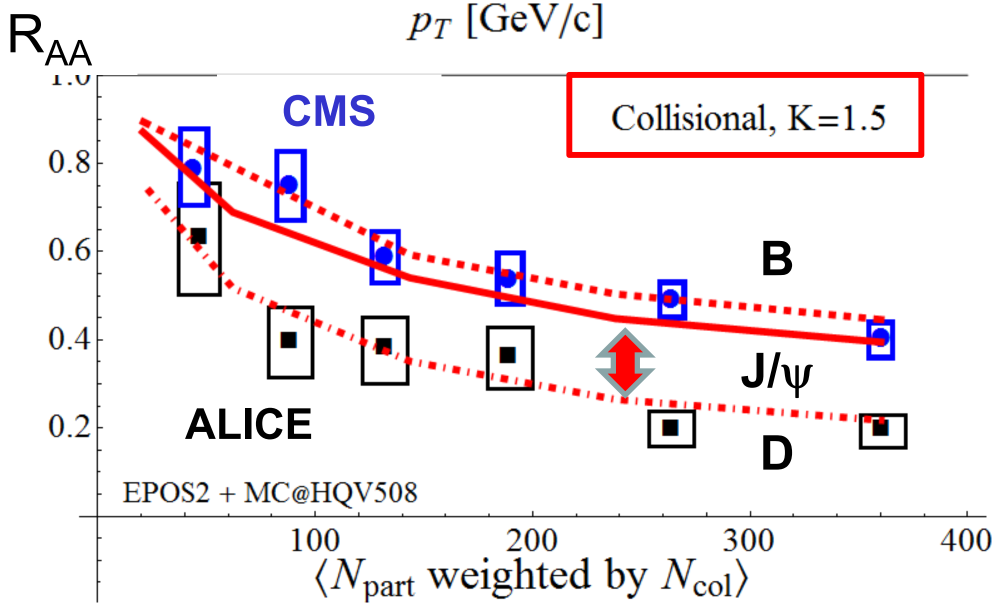


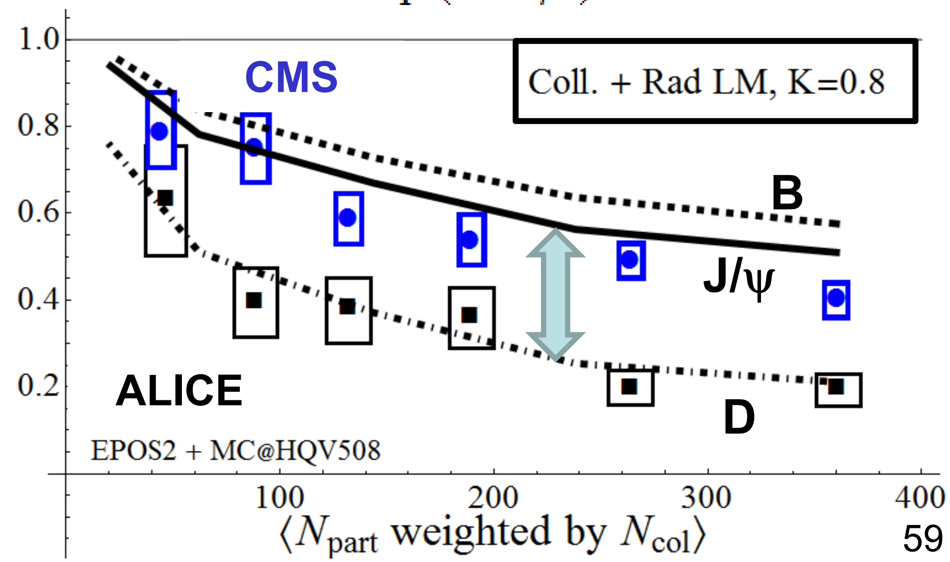
Nahrgang et al Phys. Rev. C 90, 024907 (2014)

Distinguishing btwn the models: mass dependence





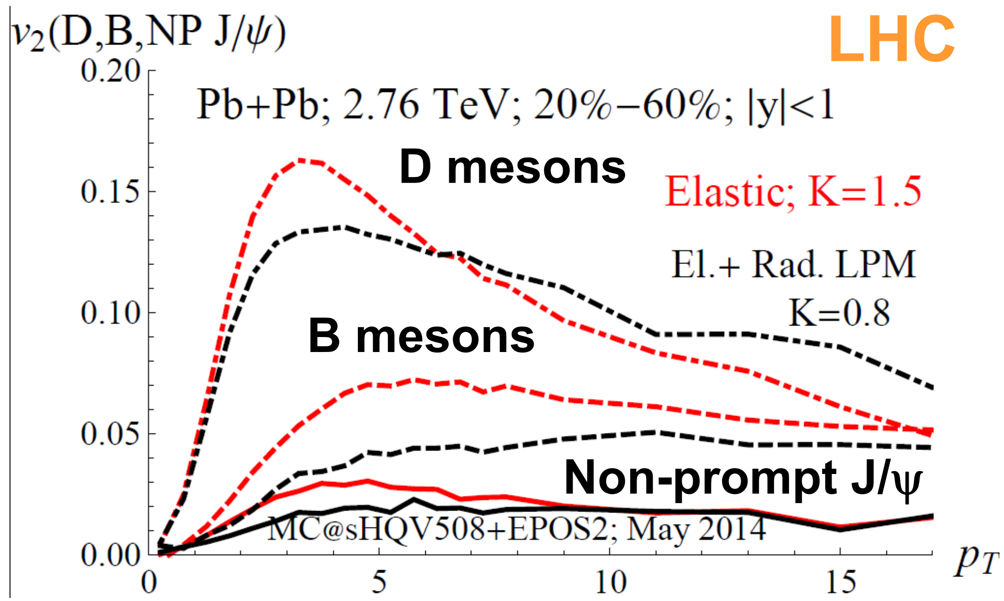


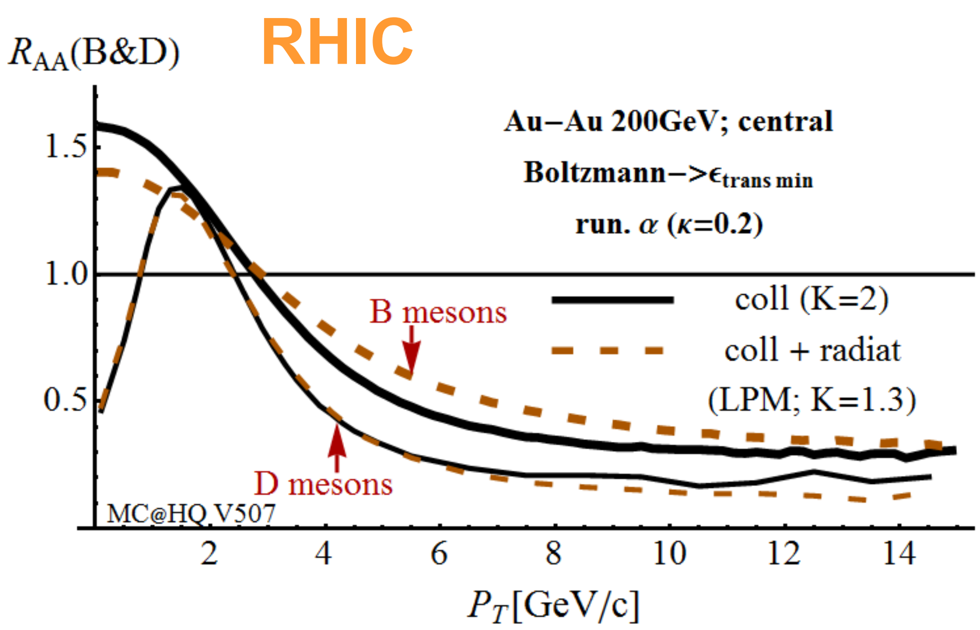


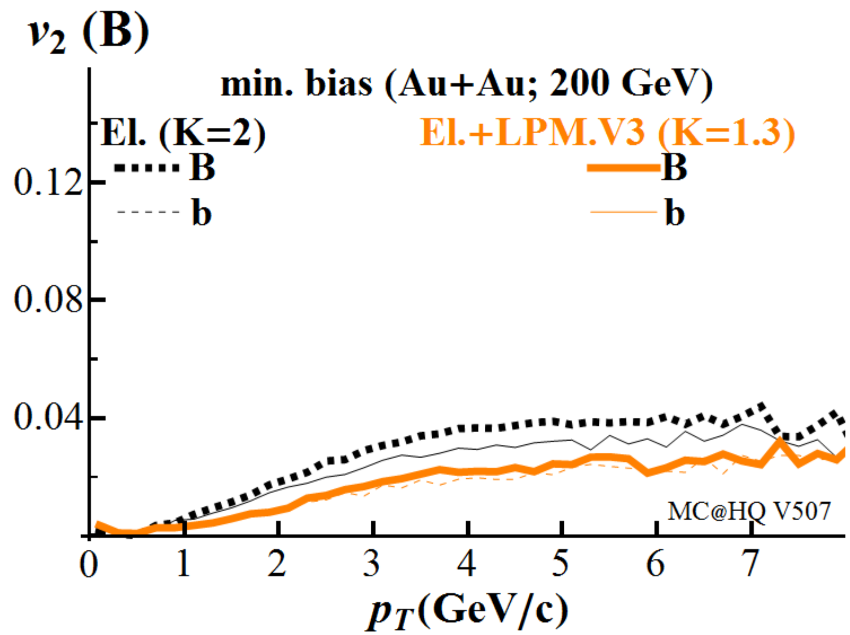
Distinguishing btwn the models: mass dependence

Predictions:

(moderate but finite difference… to be seen)

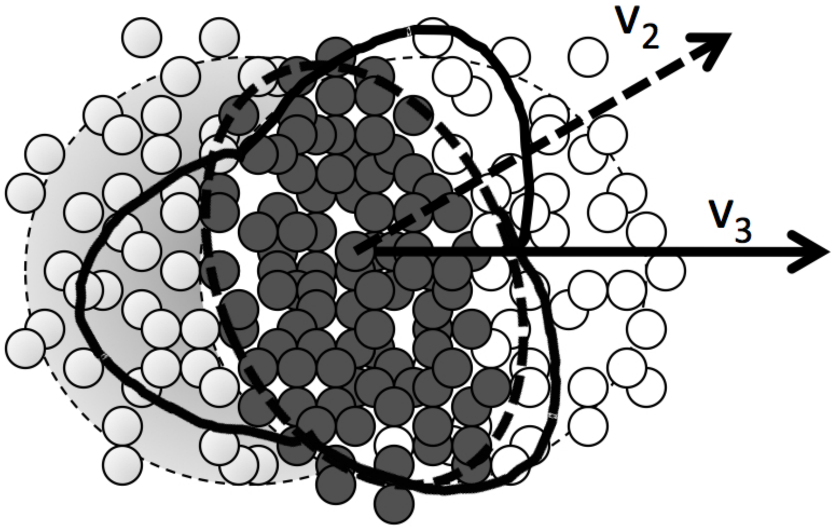




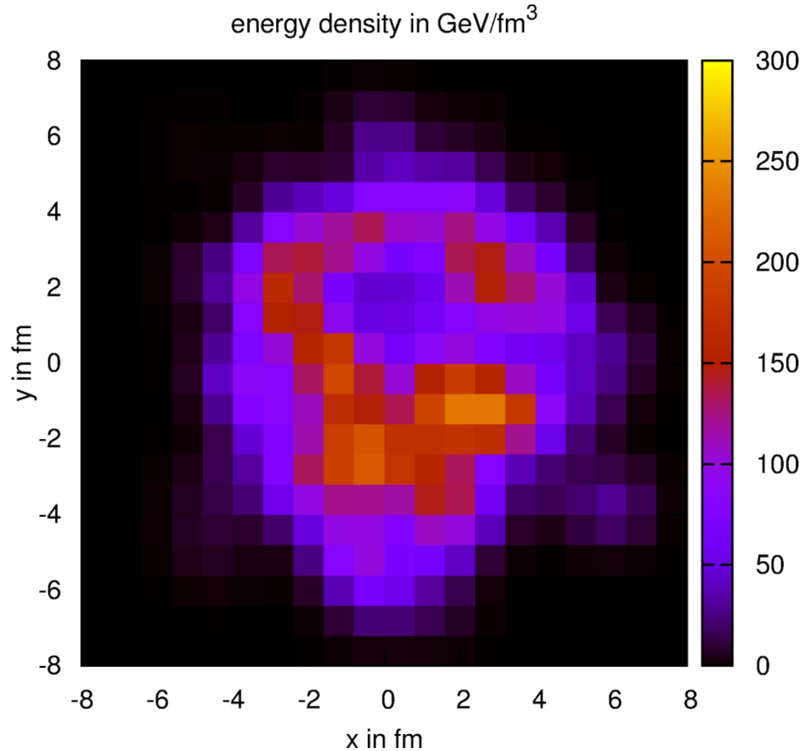


More recent observables: Higher HQ flow components

Fluctuations in the Initial energy-density profile => odd components of the flow: v_3, v_5, … (seen indeed in the light particle spectra)



sketch



EPOS initial conditions

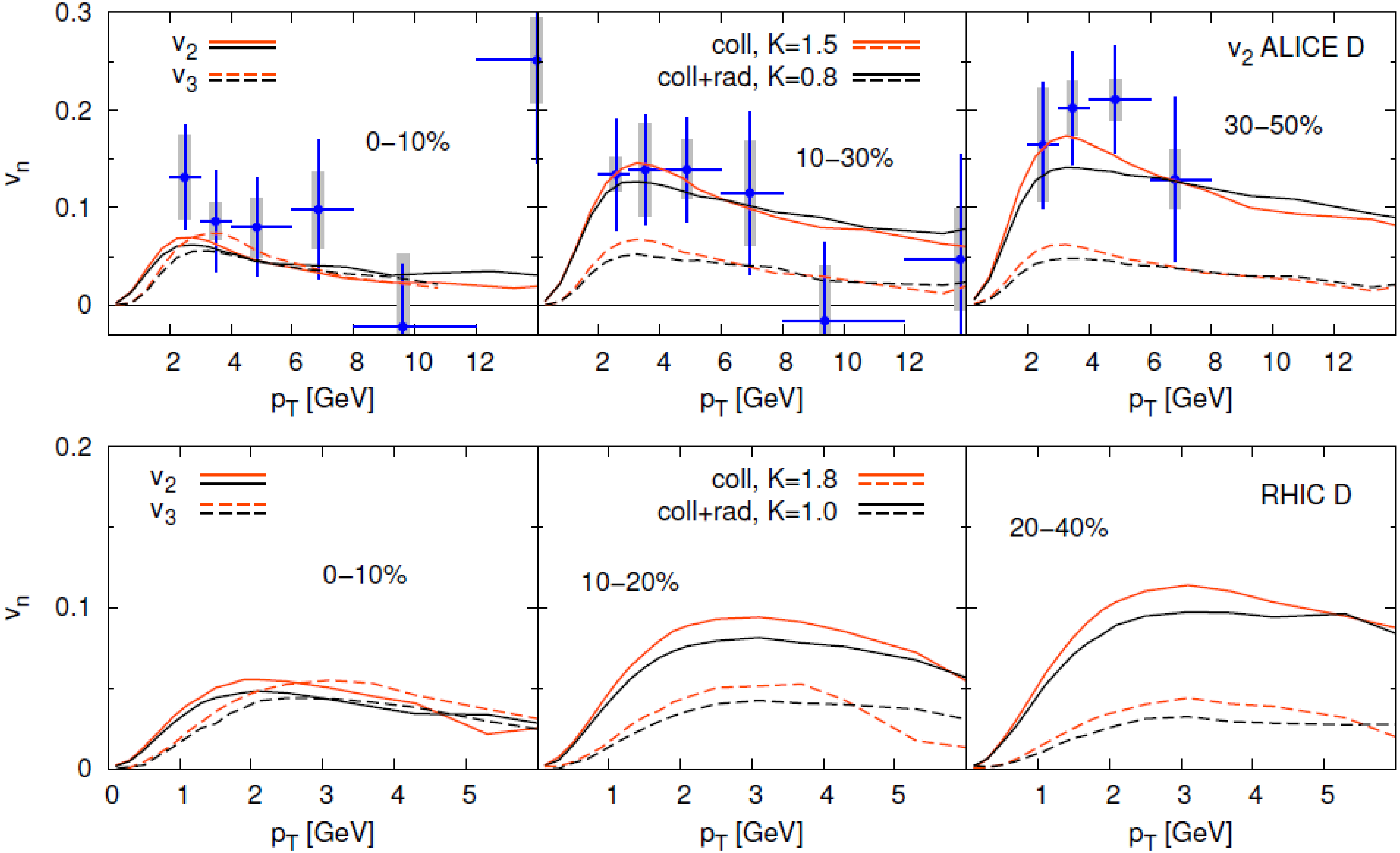
As heavy quarks couple to the expending QGP, same trend should be observed

More recent observables: Higher HQ flow components

Nahrgang et al, Phys. Rev. C 91 (2015), 014904

LHC

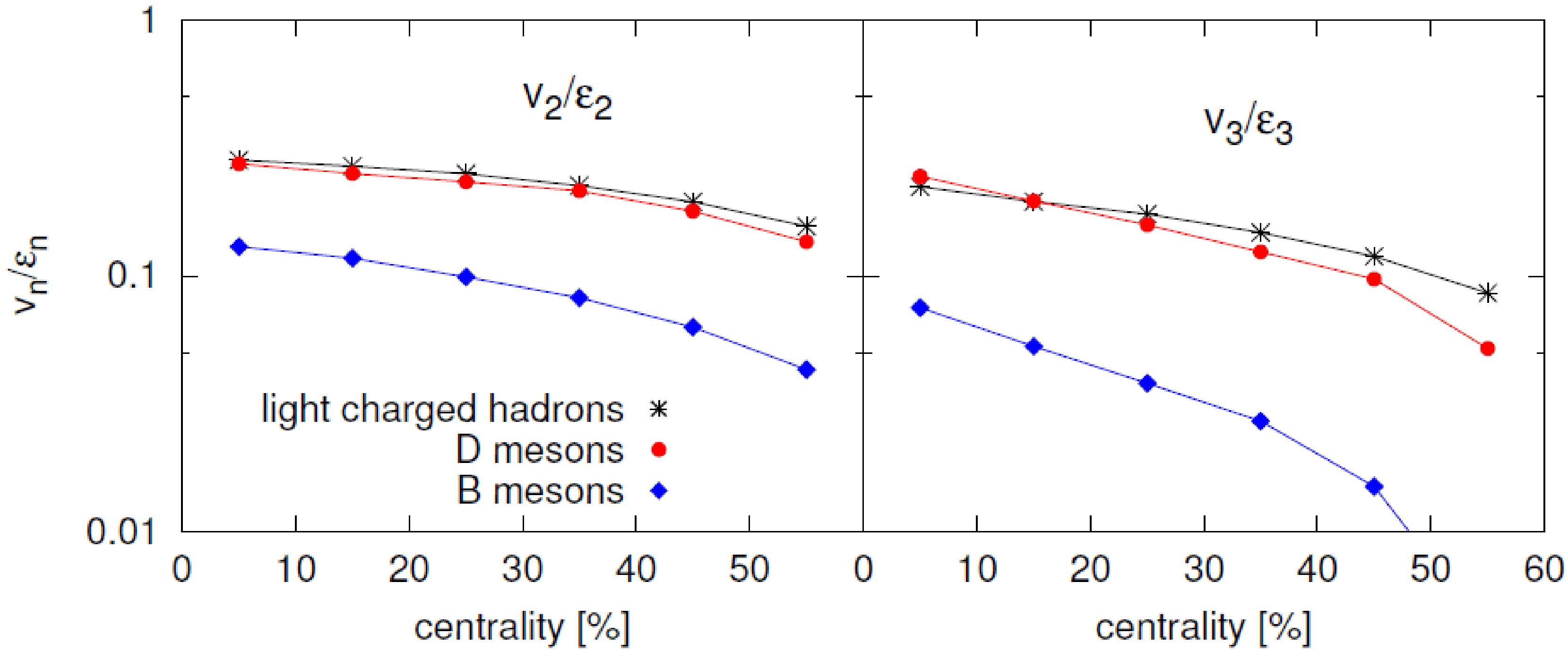
RHIC



Indeed finite v3 observed at all centralities, both at RHIC and LHC

More recent observables: Higher HQ flow components

In 1rst approximation: $v_n \alpha$ excentricity ε_n => look at the ratio for less trivial effects **LHC**



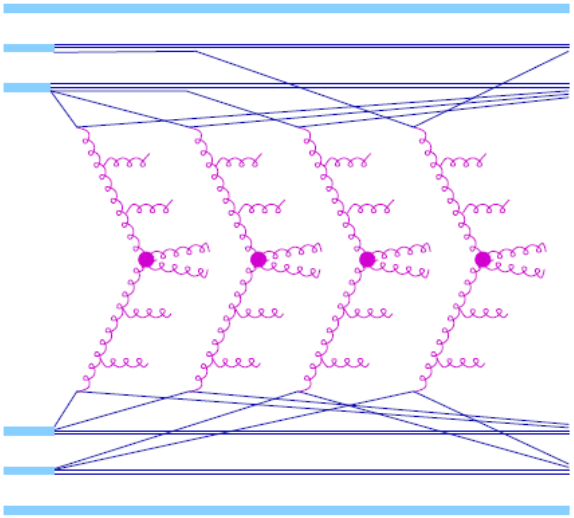
More detailed analysis reveals that HQ benefit less and less from the flow of the bulk at large centrality, especially for higher harmonics.

Possible inertia effect: HQ need a longer time to develop their flow => earlier freeze out at larger centrality prevents the v_n to develop fully.

This may offer a different perspective on the probing of the system evolution

HQ collectivity in “small” systems: the pp case at LHC.

Vogel et al. Phys. Rev. Lett. 107 (2011), 032302

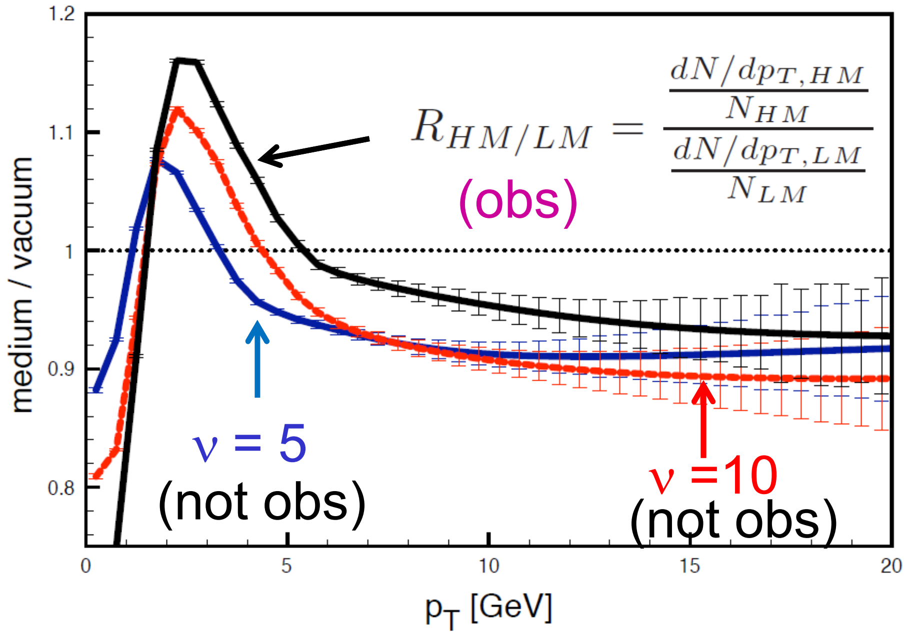


Even in p-p collisions: several (ν) pomerons exchange, up to ν =10

$$\left.\frac{dN_{\mathrm{ch}}}{dy}\right|_{y=0} \approx 29$$

Similar to Cu-Cu (RHIC)

Test whether HQ quenching in p-p

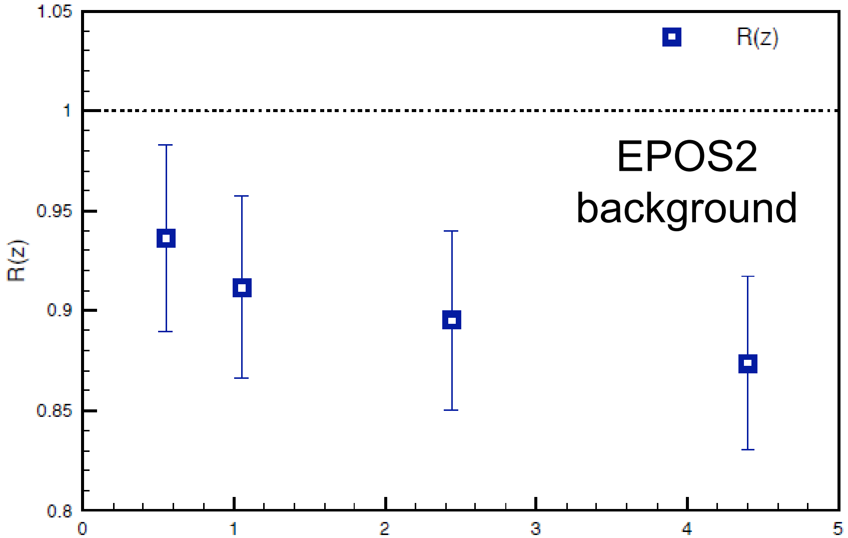


Some (10%) quenching seen indeed in the model

HQ collectivity in “small” systems: the pp case at LHC.

As a function of “centrality”

$$R(z) = \left.\frac{dN/dp_T(N_{ch})}{dN/dp_T(MB)}\right|_{p_T>10GeV} \times \frac{N_{MB}}{N_{ch}},$$



$$z = \frac{dN_{\rm ch}}{dy} / \langle \frac{dN_{\rm ch}}{dy} \rangle_{\rm MB}$$

(Self-normalizing)

HQ collectivity in "small" systems: the pp case at LHC.

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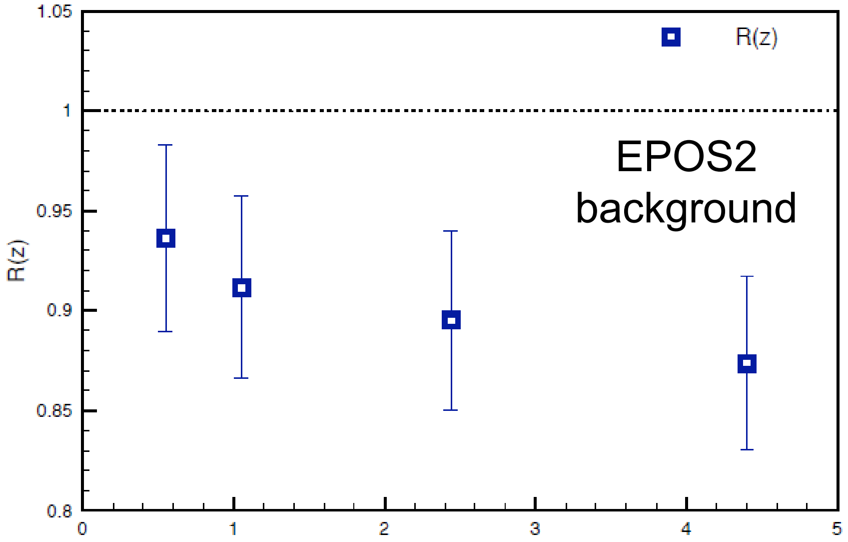
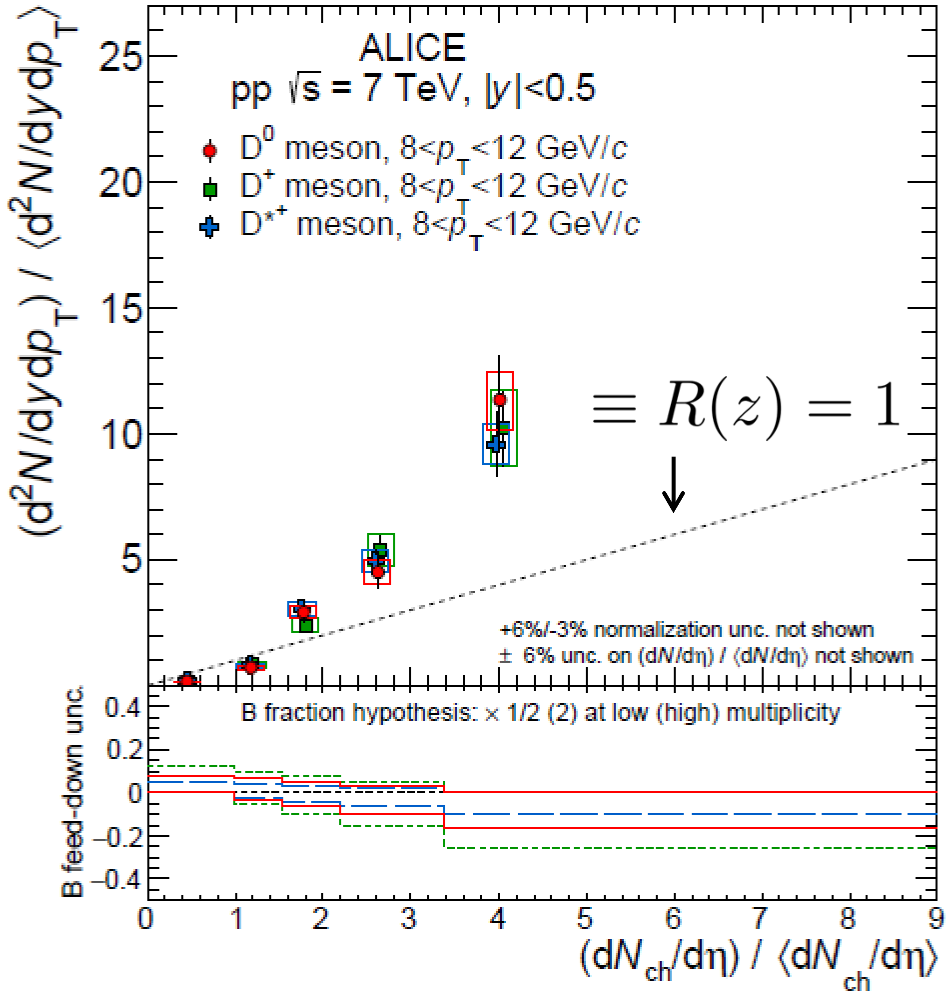


$$z = \frac{dN_{\rm ch}}{dy}/\langle\frac{dN_{\rm ch}}{dy}\rangle_{\rm MB}$$

(Self-normalizing)

Opposite trend seen in data…

ALICE (arxiv 1505.00664)



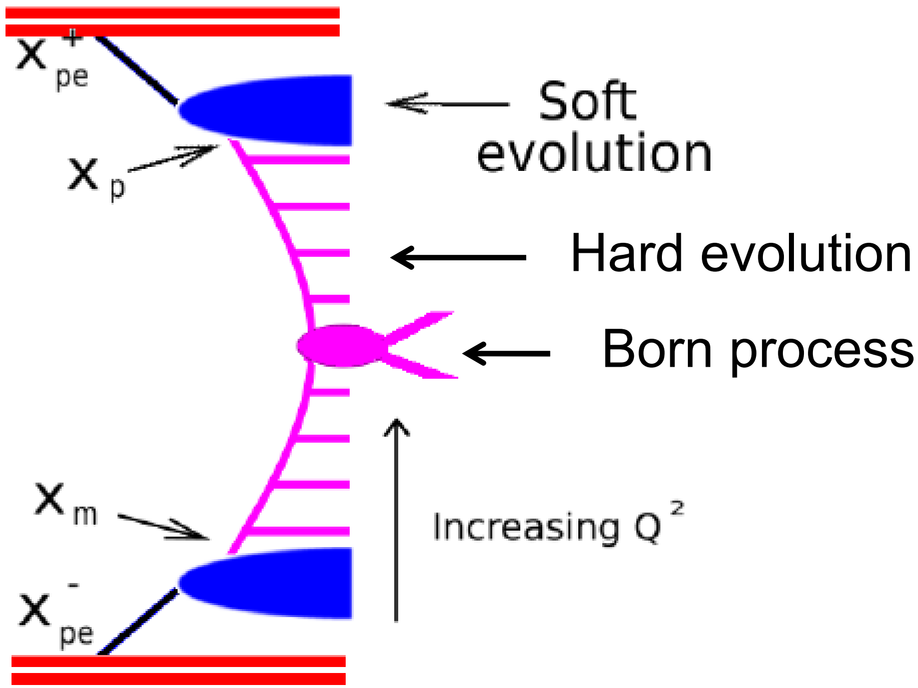
$\equiv R(z) = 1$

(b) D meson with $8 < p_T < 12$ GeV$/c$

HQ in EPOS

Generating initial HQ consistently with the multi-partonic approach in EPOS (done in EPOS3; B. Guiot)

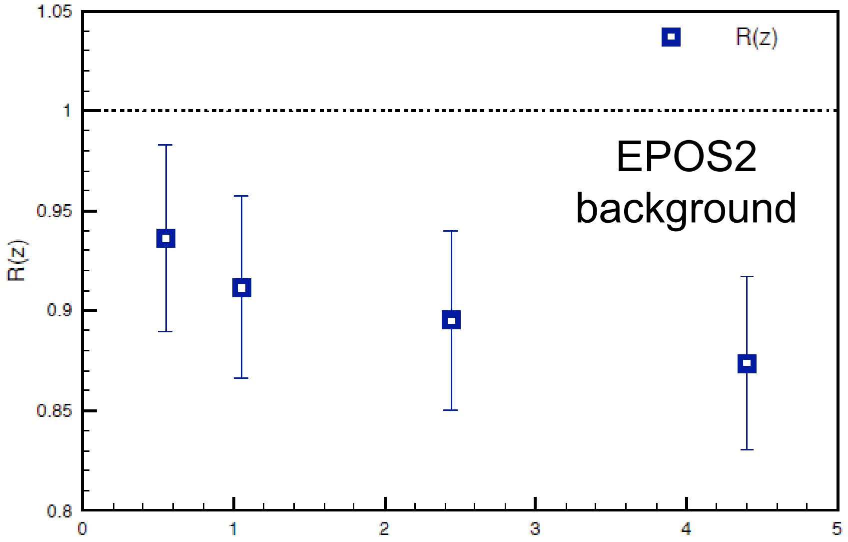
… But not HF-QGP coupling



HQ collectivity in “small” systems: the pp case at LHC.

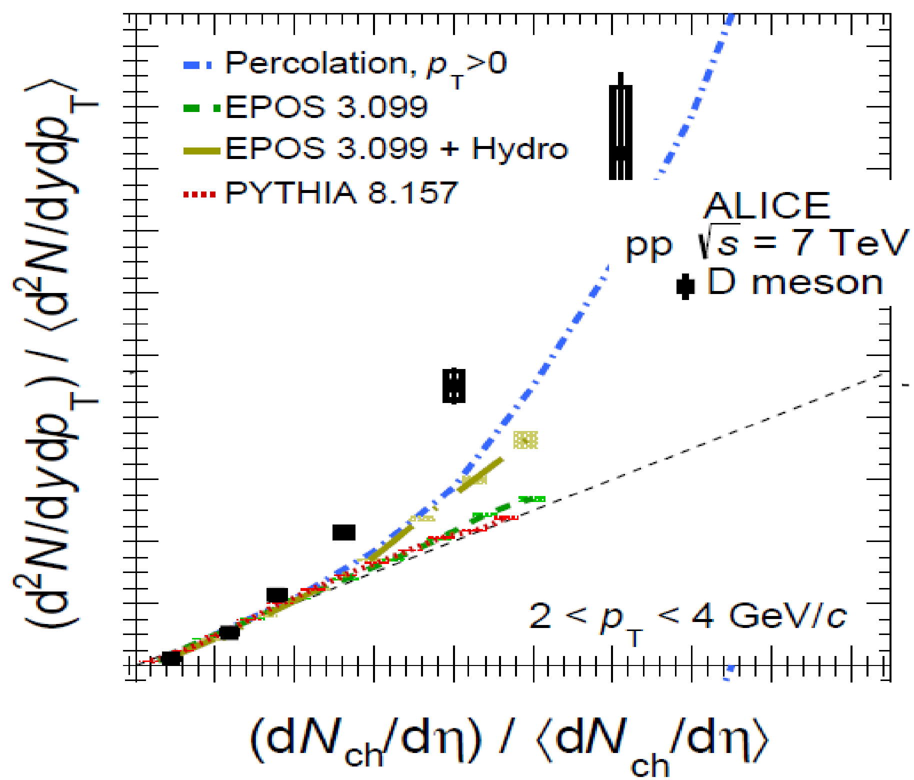
As a function of “centrality”

$$R(z) = \left.\frac{dN/dp_T(N_{ch})}{dN/dp_T(MB)}\right|_{p_T>10GeV} \times \frac{N_{MB}}{N_{ch}},$$



$$z = \frac{dN_{\rm ch}}{dy} / \langle \frac{dN_{\rm ch}}{dy} \rangle_{\rm MB}$$

(Self-normalizing)



Opposite trend seen in data…

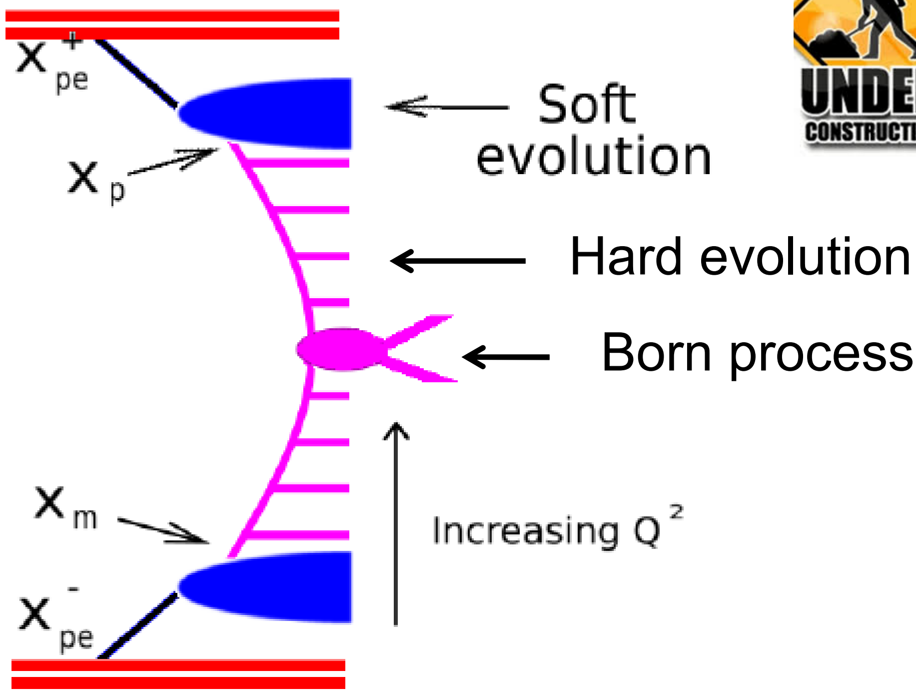
(Working hypothesis: N_{ch} α ν, but hydro created in pp leads to a strong reduction)

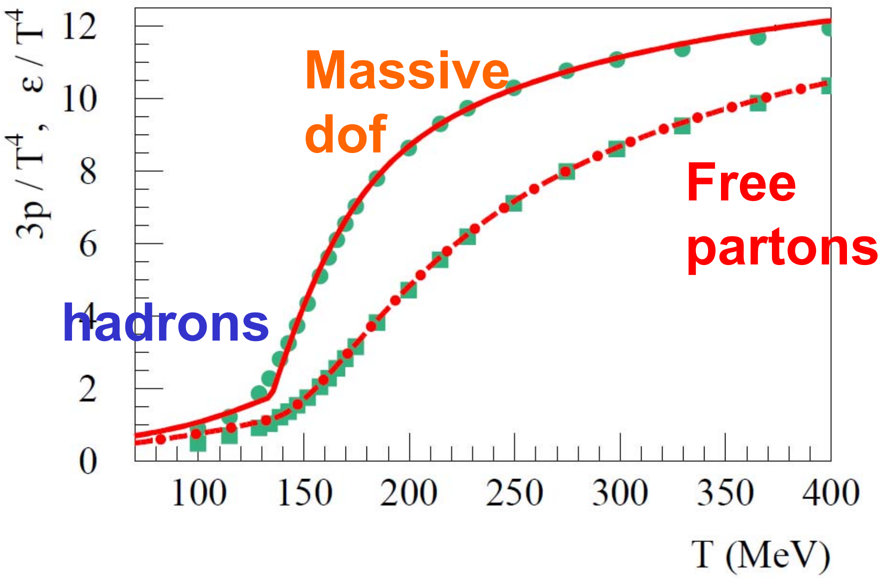
Good lesson for us: do not just take EPOS “as a background”

EPOS-HQ: Coupling EPOS3 and MC@sHQ

Two main (physical) issues:

1) Generating initial HQ consistently with the multi-partonic approach in EPOS (done in EPOS3; B. Guiot)

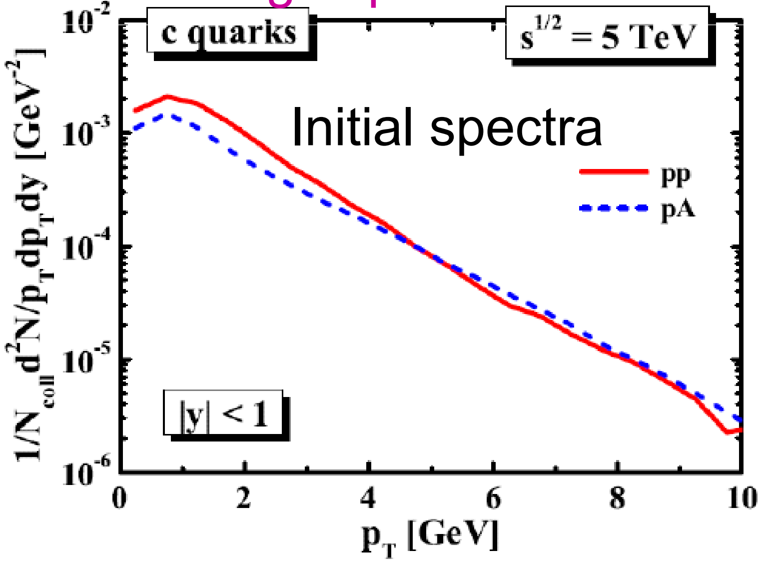




2) Dealing properly with the underlying degrees of freedom in a crossover evolution btwn hadronic phase and QGP.

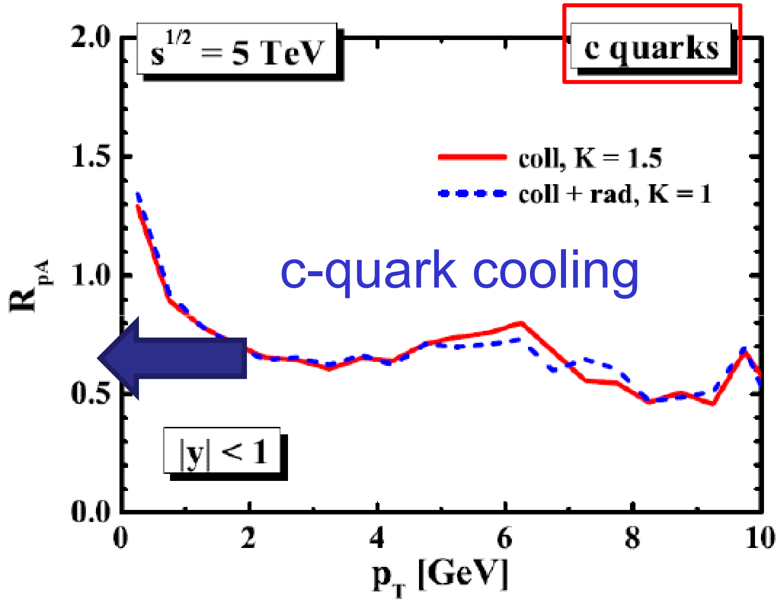
2015: HQ collectivity in p-Pb at LHC.

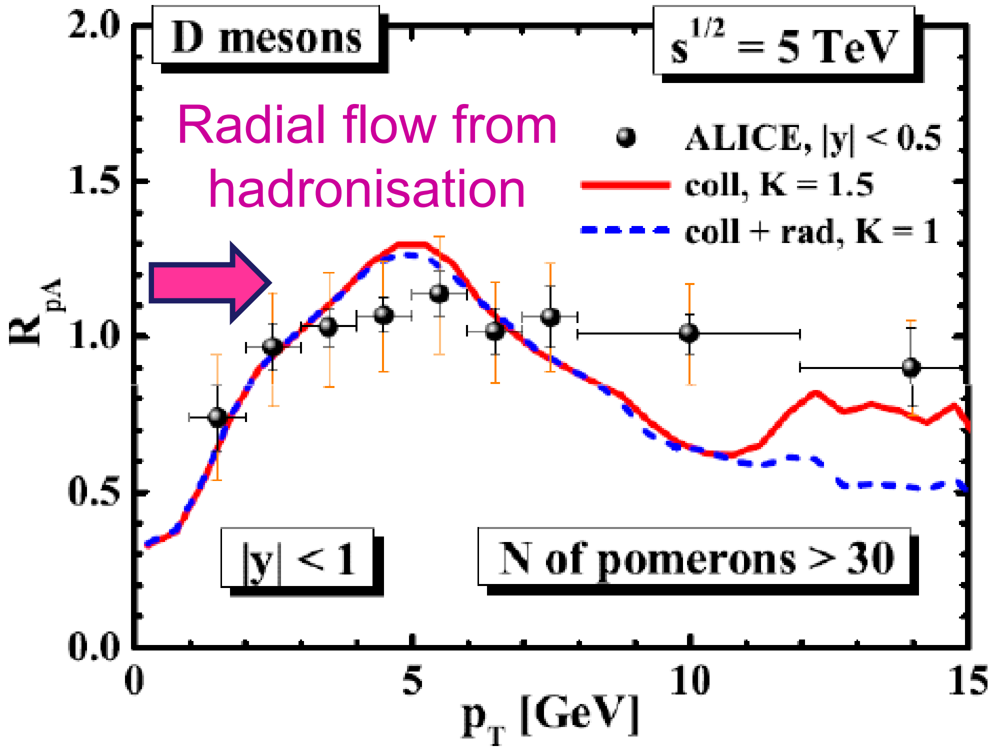
Shadowing implemented in EPOS3



Vitalii Ozvenchuk, 2nd Conference on HIC in the LHC Era and Beyond (Quy Nhon, Vietnam)

Very preliminary





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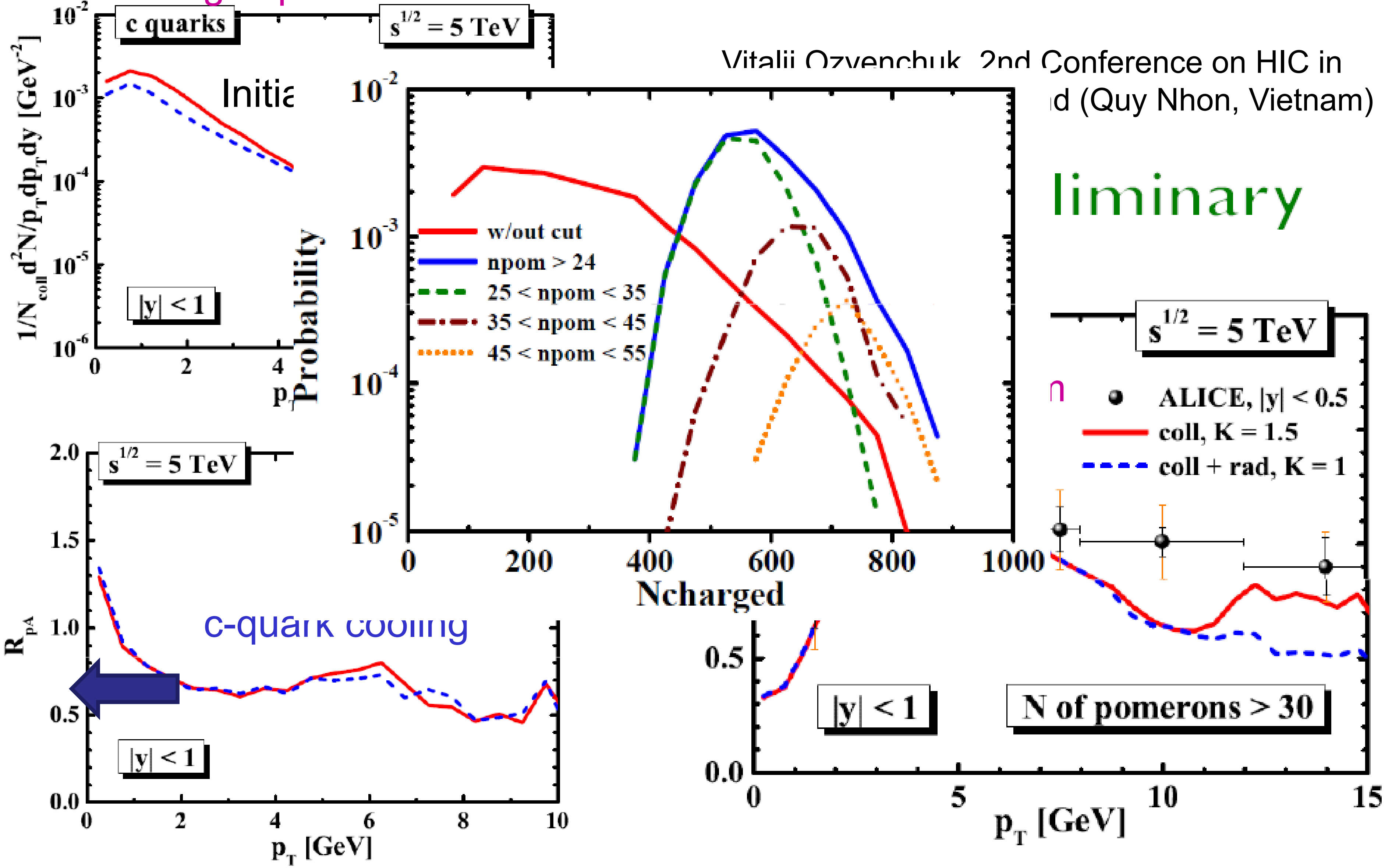
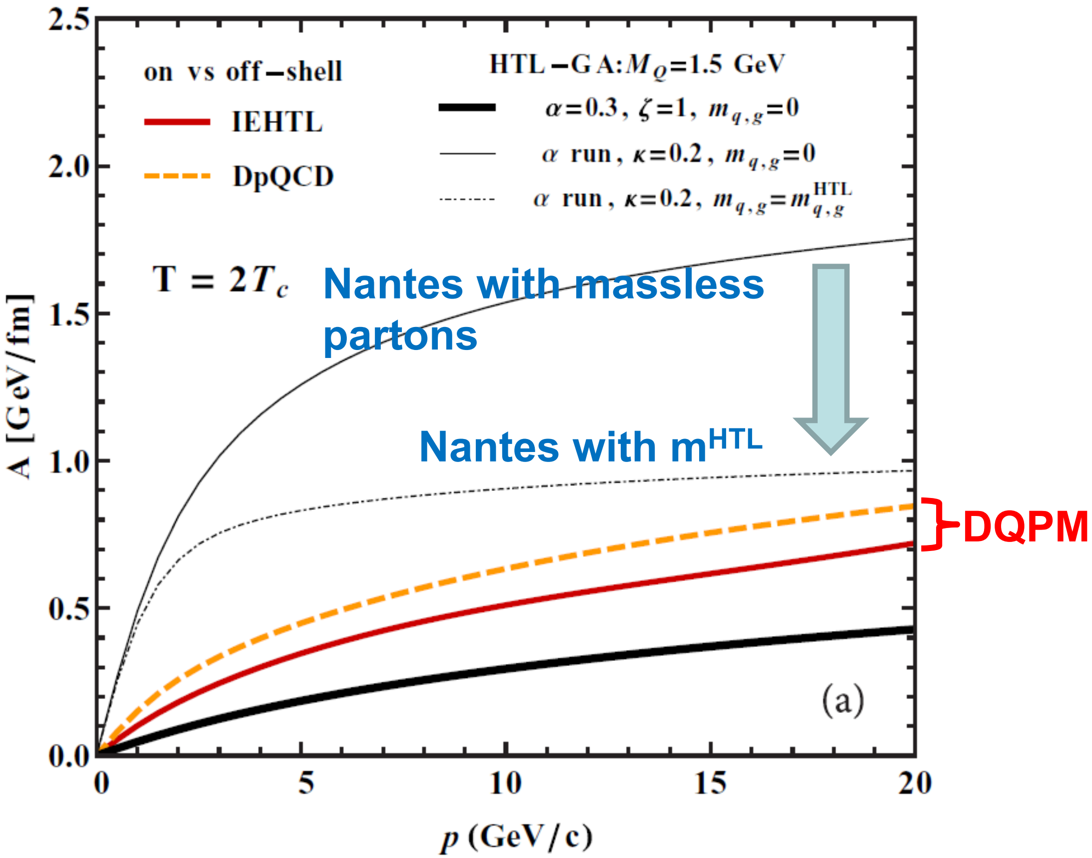
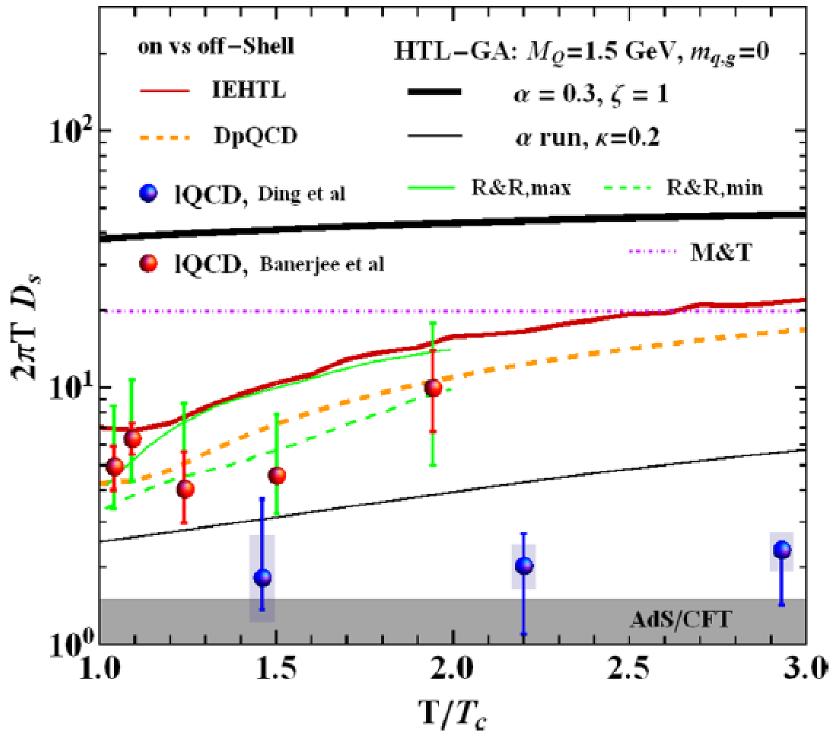


Effect of (light) parton thermal mass

In all previous results: all scattering **light** partons assumed to be massless; HQ evolution stopped at T=168 MeV

PHYSICAL REVIEW C **90**, 064906 (2014)



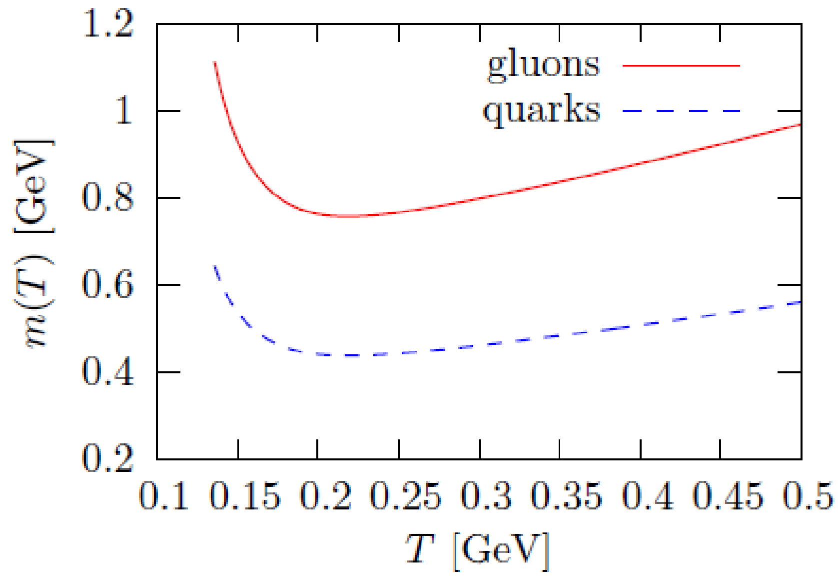


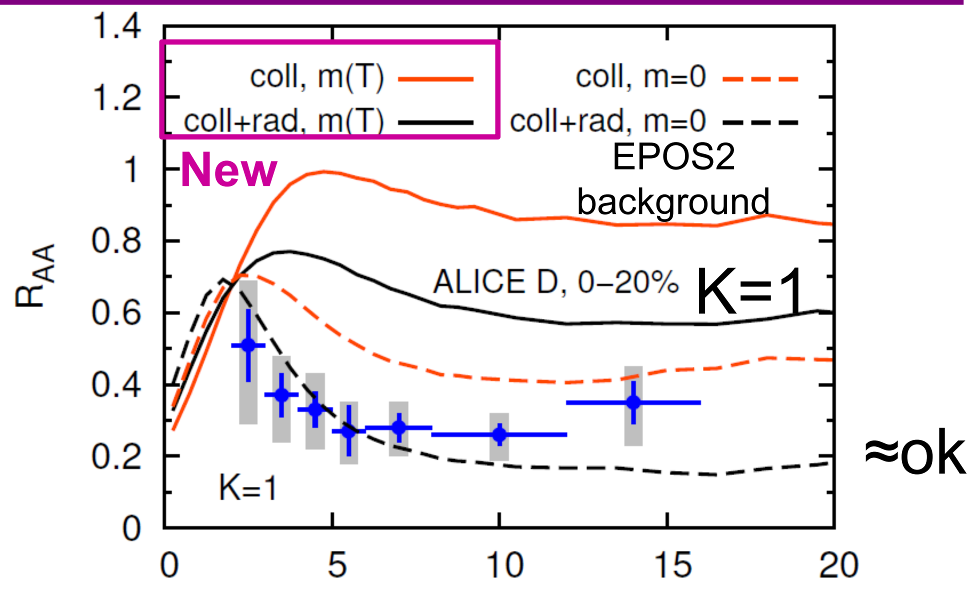
All models in the bulk part of lattice data

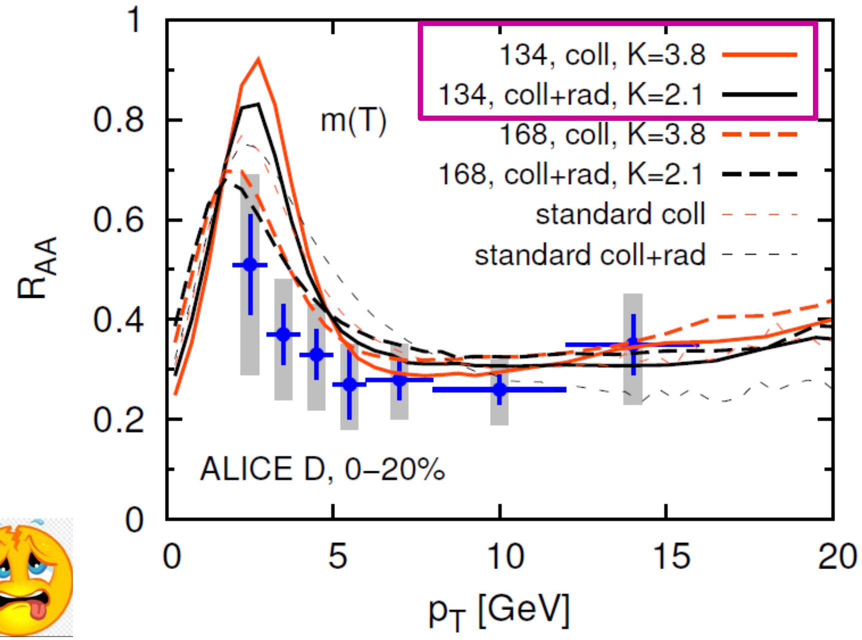
… but those are just models (beware of broken gauge invariance)

Effect of (light) parton thermal mass

Nahrgang et al. PRC93 (2016), 044909: extracting masses from lattice EOS



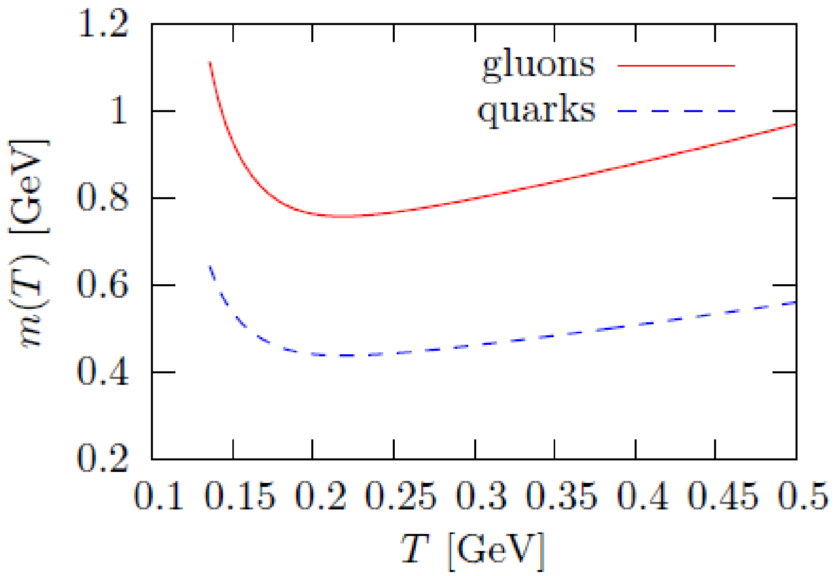




With m(T), need to cranck up the interaction by a factor 2 in order to be compatible with the LHC data !!! No way to depart from our « strongly coupled » band if we want to stick to the data…

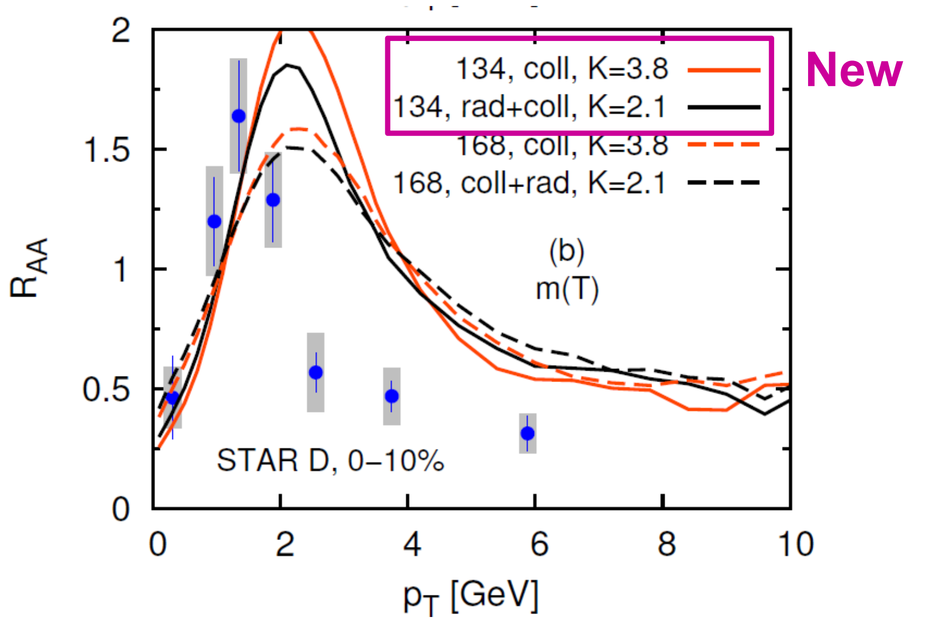
Effect of (light) parton thermal mass

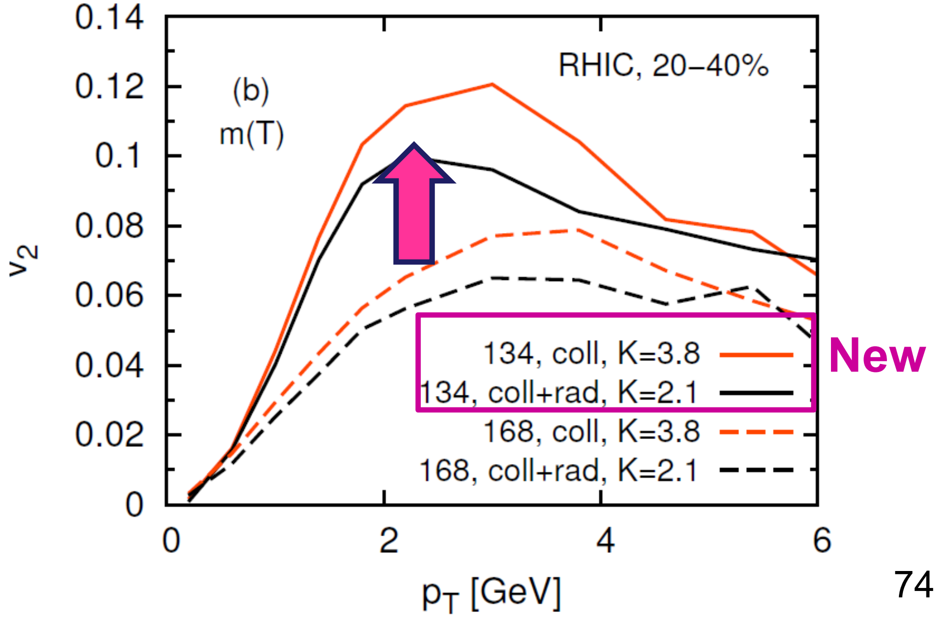
Nahrgang et al. PRC93 (2016), 044909: extracting masses from lattice EOS



Late stage of the evolution: large increase of v_2

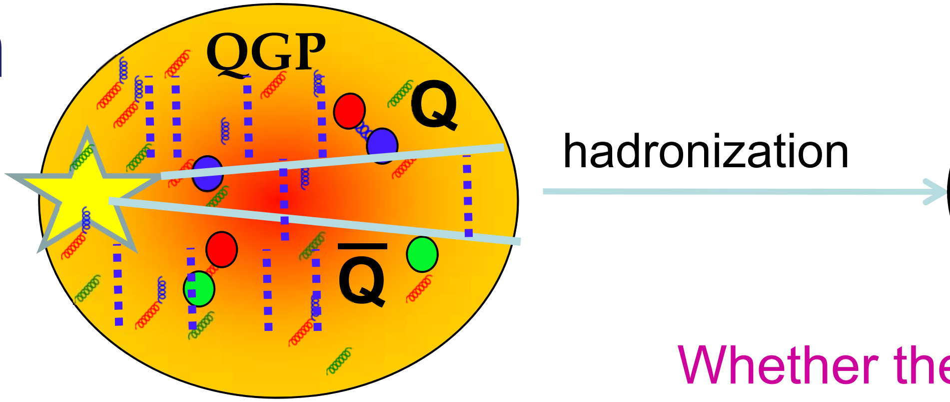
!!! EPOS2 background (ideal hydro) !!! EPOS-HQ expected to be back on the data

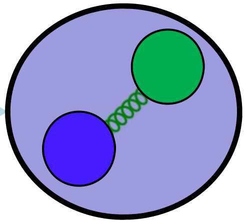




Back to quarkonia (upsilon focused)

Motivation





Very complicated QFT problem at finite T(t) !!!

No independent Υ(1S), Υ(2S),.. evolution during QGP history

Whether the $Q\bar{Q}$ pair emerges as a quarkonia or as open mesons is <u>only resolved at the end of the evolution</u>

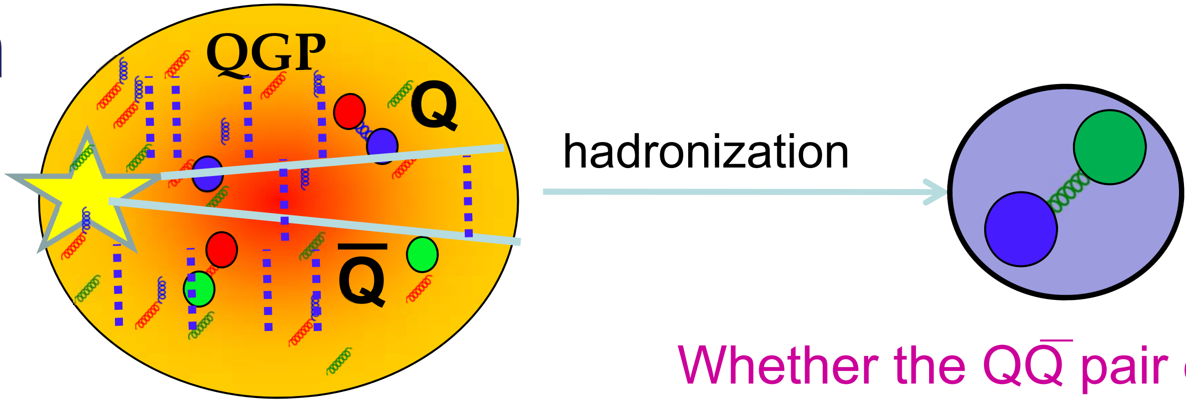
Beware of quantum coherence during the evolution !

Need for full quantum treatment

Dating back to Blaizot & Ollitrault, Thews, Cugnon and Gossiaux; early 90's

Back to quarkonia (upsilon focused)

Motivation



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Schrödinger-Langevin (SL) equation

$$\boxed{i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}_{\mathrm{MF}}(\mathbf{r}) - \mathbf{F}_{\mathbf{R}}(t).\mathbf{r} + A\big(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big)\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)}$$

Mean Field

Stochastic forces

Damping (**connected with the OHF friction coefficient**)

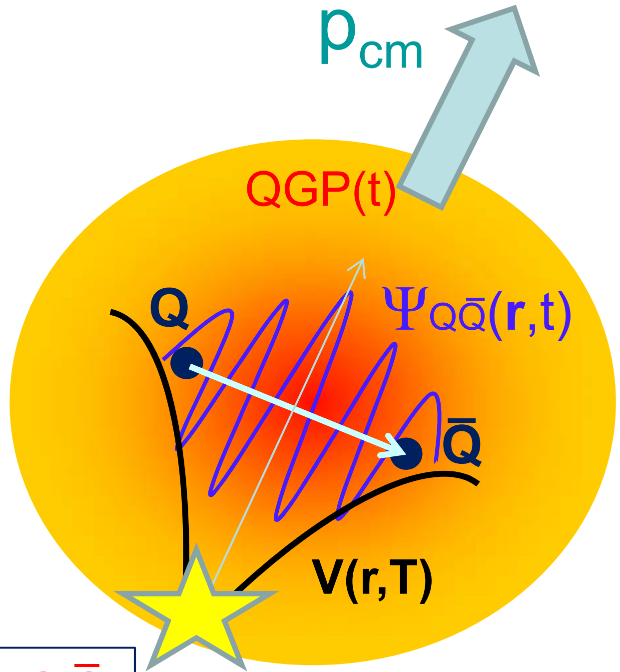
R. Katz and PB Gossiaux
Annals of Physics 368 (2016), 267

Back to quarkonia (upsilon focused)

Ingredients for a generic model

QGP temperature scenarios T(t,x)

Cooling QGP
(for the time: EPOS 2)



Initial $Q\bar{Q}$ state

Mean field: color screened binding potential V(r,T)

polarization due to color charges

+

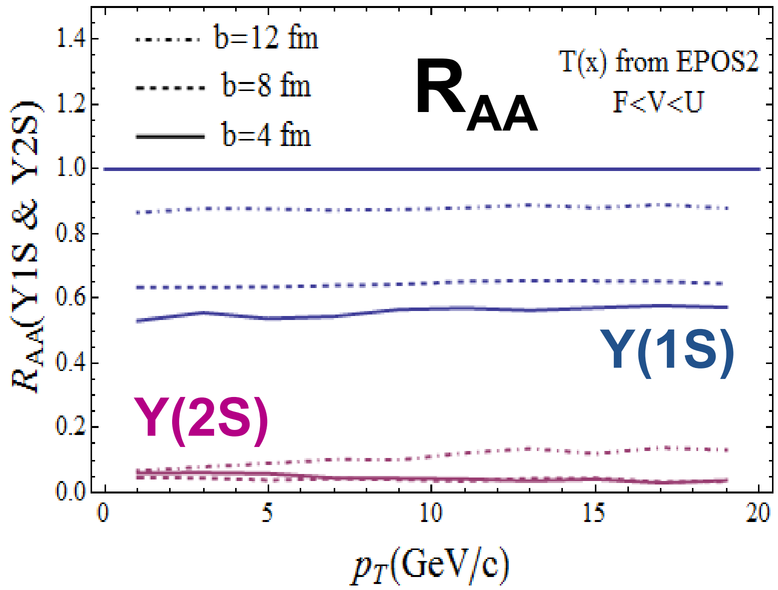
Thermalisation and diffusion

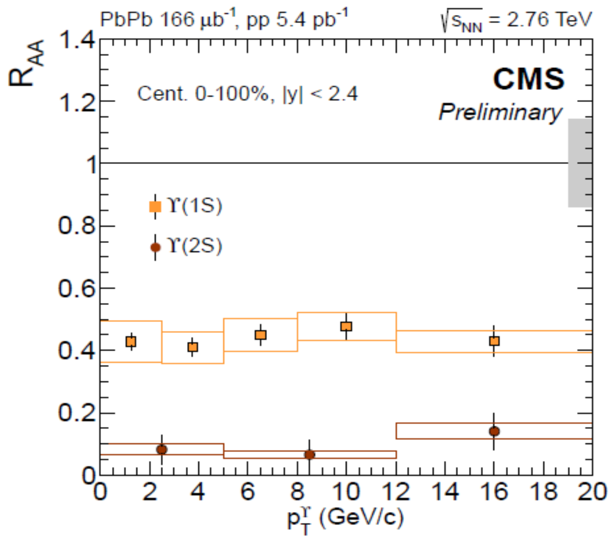
Direct interactions with the thermal bath

+ Schrödinger-Langevin (SL) equation

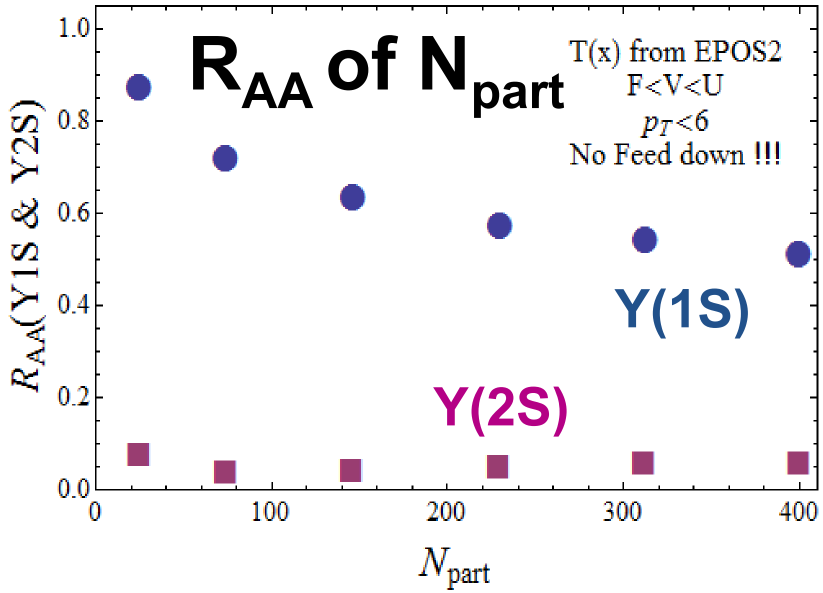
Final Upsilon suppression in Pb-Pb (2.76 TeV)

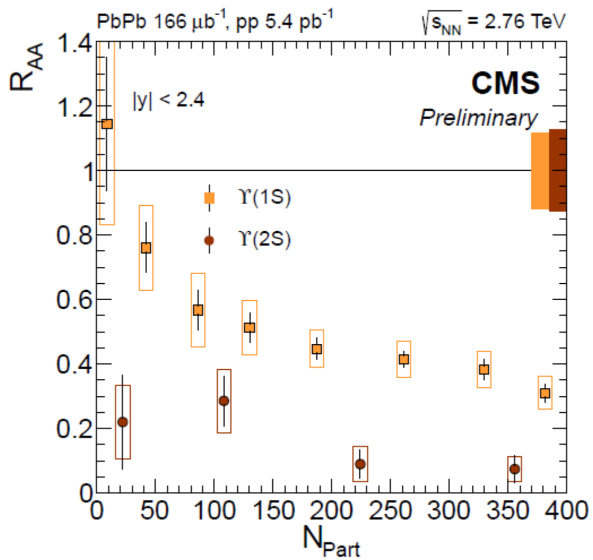
Flatish $R_{AA}(p_T)$, except for the Y(2S) in peripheral collisions





F<V<U seems to be preferred by comparison with the data



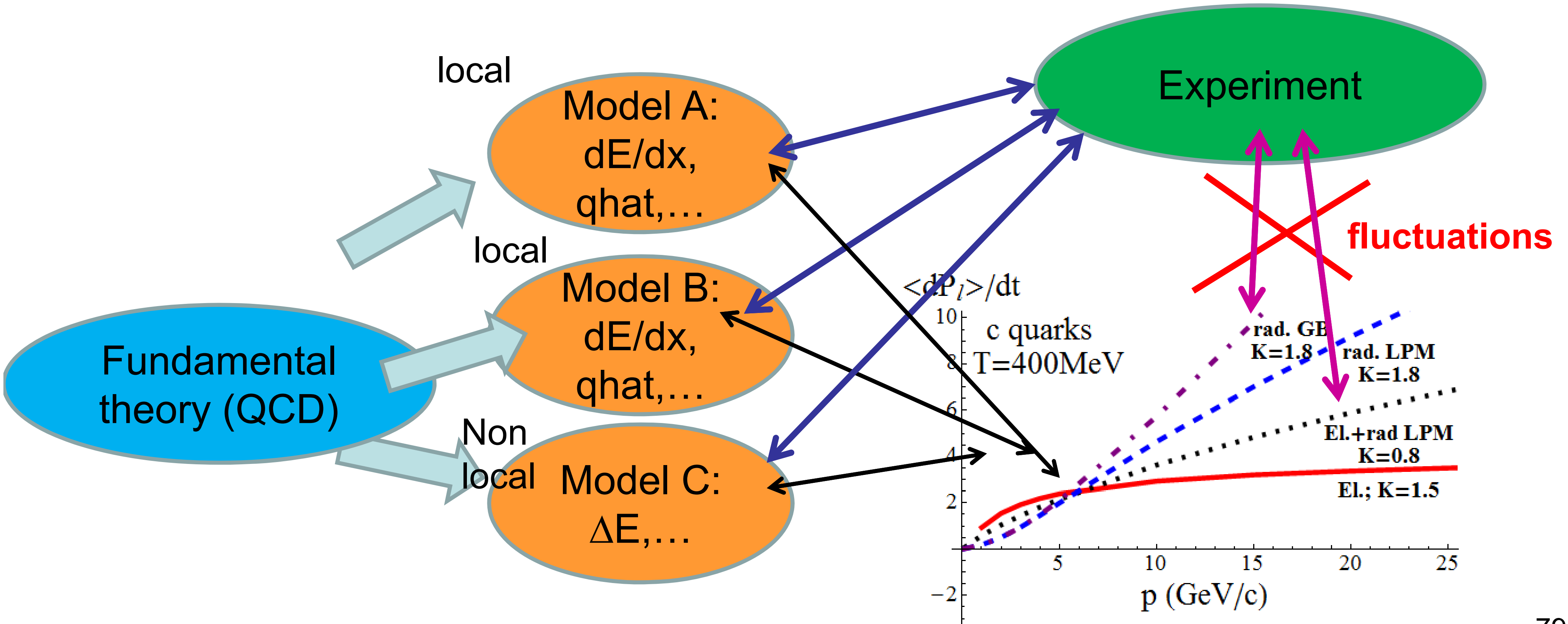


For more details:
R. Katz and PB Gossiaux
arXiv:1601.01443

Conclusions

Despite all progresses made in the field of URHIC probing the "quark gluon soup" with heavy flavour and assessing unambiguously its physical properties is still a delicate task.

This is partially due to the abundance of models and the lack of constrains from the fundamental theory



Conclusions

Despite all progresses made in the field of URHIC probing the “quark gluon soup” with heavy flavour and assessing unambiguously its physical properties is still a delicate task.

This is partially due to the abundance of models and the lack of constrains from the fundamental theory

But also to the large variety of ingredients adopted in the global scenario (including the background medium)

Collaborative work is the only way out

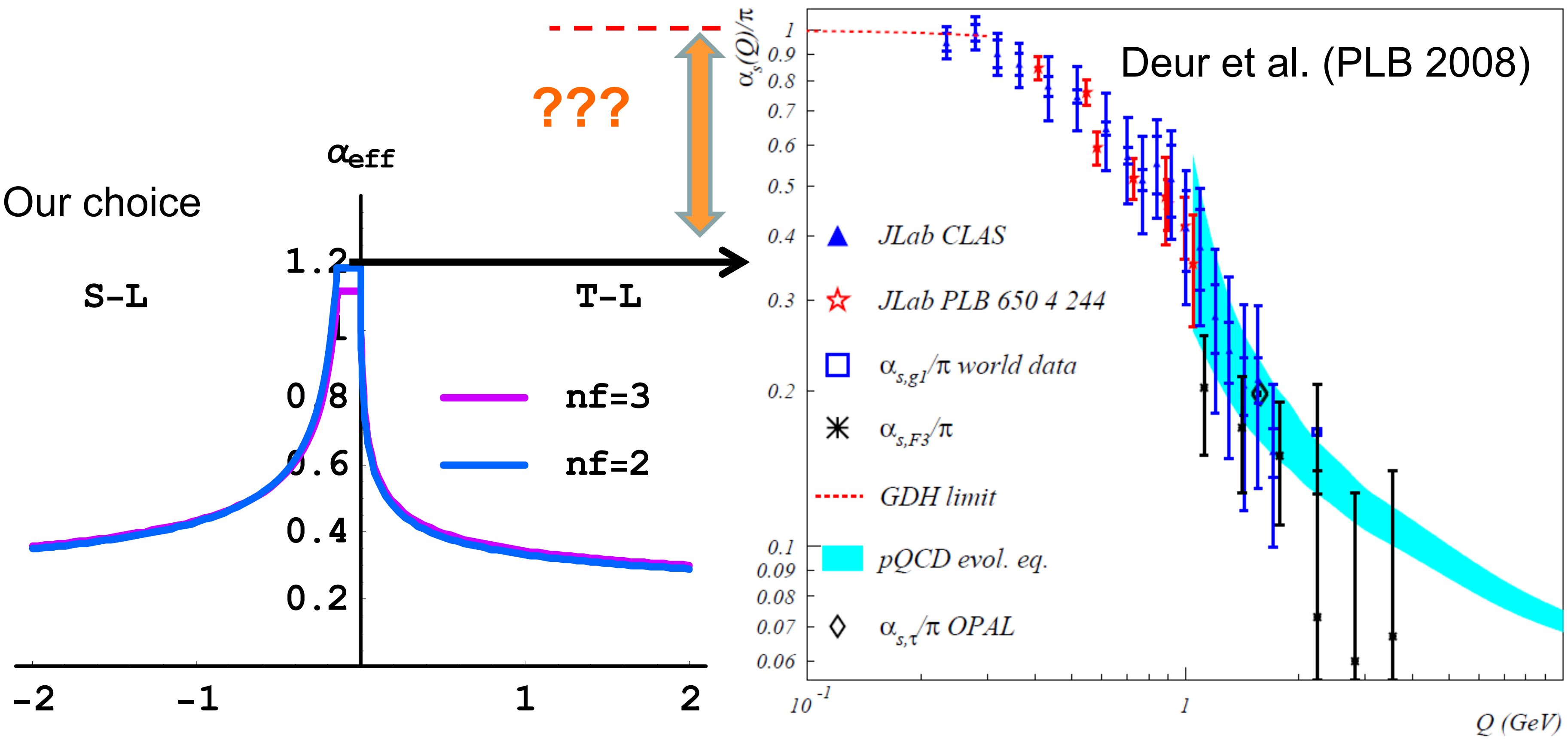
What is good one day might be bad the next one and vice versa (keep on the job !)

Not included

- **Influence of the hadronic phase**
- **Influence of hadronisation**
- **CNM effects**

Elastic Eloss @ RHIC

We "explain" it all provided we allow for a multiplication of our pQCD (inspired) cross section by a factor 2



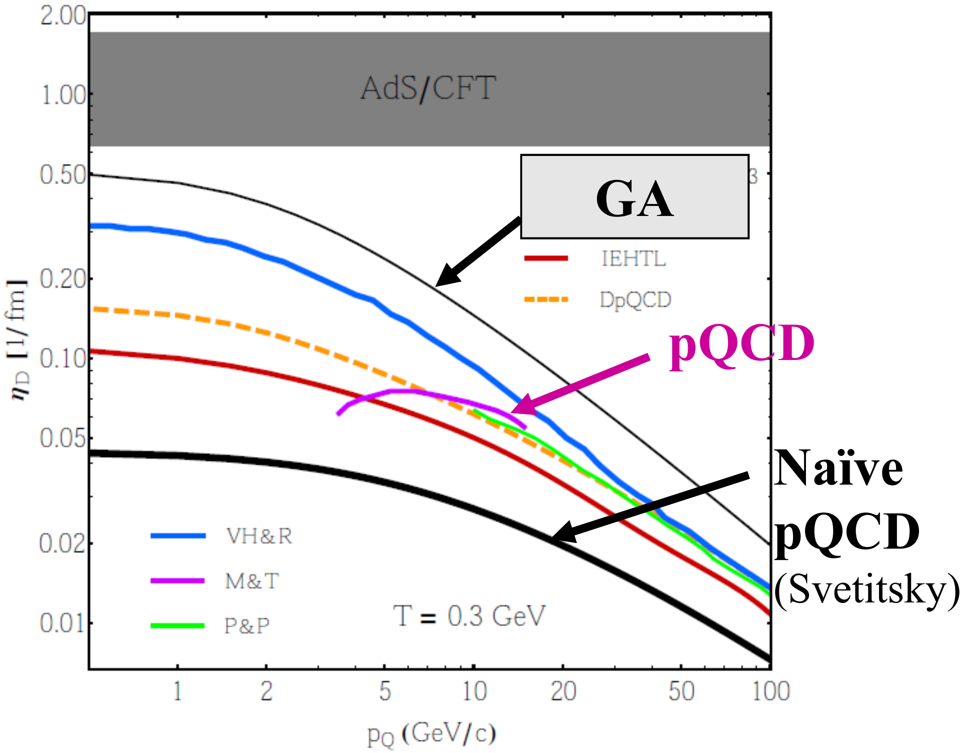
Running α_s : some Energy-Loss values

$$\frac{dE_{coll}(c/b)}{dx}$$

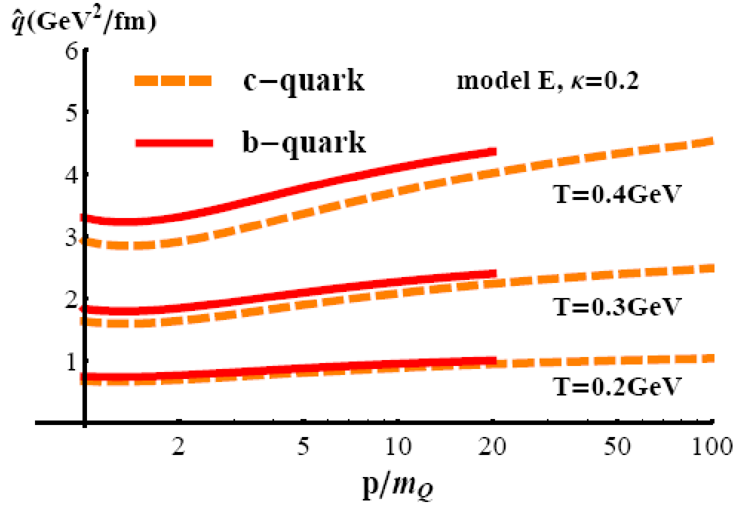
T(MeV) \p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient (inverse relax. time)



Transport Coefficient



… of expected magnitude to reproduce the data (we “explain” the transp. coeff. in a rather parameter free approach).